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CALCULATING METHOD FOR MULTI-STAGE
AXIAL COMPRESSORS WITH IMPULSE
BLADINGS AND CONSTANT TIP DIAMETER

M. H. Vavra

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Monterey, California

Rear Admiral Mason Freeman
Superintendent

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The report was prepared to permit evaluations of the applicability of such compressors in advanced propulsion units for air-superiority aircraft, or in light-weight lift engines for military VTOL aircraft.

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SUMMARY

This report gives an approximate calculating method for the design point performance of multi-stage axial compressors with impluse-type bladings and constant tip diameters. Computing programs for Monroe-1800 programmable calculators are presented to establish the compressor performance and the blading parameters for arbitrary conditions with minimum effort.

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CALCULATING METHOD FOR MULTI-STAGE
AXIAL COMPRESSORS WITH IMPULSE
BLADINGS AND CONSTANT TIP DIAMETER

by

M. H. Vavra

1. INTRODUCTION

Impulse-type stages of the type shown in Figs. 1 and 2 are presently used for fan stages of by-pass jet engines. Considerable progress has been made in their performance at supersonic Mach numbers of the relative inlet velocity W_1. Reference 1 shows that at a tip Mach number of 1.43 it was possible to obtain rotor efficiencies close to 90 percent for total pressure ratios of the rotor of 1.7.

Second generation propulsion units for air-superiority Navy aircraft of the F-14 type will require overall pressure ratios of 30 and higher to produce the desired thrusts with acceptable fuel consumption, without increasing the diameter of the presently installed engines. To save weight it is imperative that compressors are available which can produce high pressure ratios with as few stages as possible. It is necessary, on the other hand, that their efficiencies are as high as or better than those of existing compressors. The possibility exists that compressors of the type considered can satisfy these requirements.

Multi-stage impulse-type compressors at elevated Mach numbers with high pressure ratios and efficiency could also be used in so-called lift engines for VTOL aircraft which must have very large thrust/weight ratios.

In a previous report (Ref. 2) a calculating procedure has been established for the performance evaluation of engines for air-superiority aircraft. With

1. Gostelow, J. P., "Design and Performance Evaluation of Four Transonic Compressor Rotors", ASME, Journal of Engineering for Power, January 1971, pp. 3/41.

Ref. 2 it will be possible to arrive at typical compressor specifications for the two applications with systematic changes of the various design parameters. The present report will then be used to calculate the dimensions and design particulars of suitable impulse-type compressors, and show what areas of ignorance must be clarified to reach the full potential of this type of compressor.

The ultimate purpose of the whole study is to examine whether research and development work in multi-stage impulse-type compressors is warranted, and if so, whether the facilities of the Propulsion Laboratory of the Naval Postgraduate School would be suitable for this endeavor. The results obtained by the study would then form the basis for a research program with well defined goals for particular compressors for specific Naval applications.

2. GENERAL CONCEPTS AND ASSUMPTIONS

The presented calculating method for multi-stage impulse-type compressor is limited to designs where all stages have the same outer diameter, and where the axial through-flow velocities of a stage vary from inlet to discharge. In particular, with the symbols of Fig. 3,

$$\frac{V_{a2}}{V_{a1}} = \frac{V_{a3}}{V_{a2}} = \lambda \tag{1}$$

where λ is smaller than unity to produce low axial velocities after the last compressor stage.

The principal variable parameters of impulse bladings are the relative tip flow angle β_{1T}, the rotor tip diffusion factor D_{RT}, the cascade solidity σ_{RT} at the rotor tip, and the peripheral rotor tip speed U_T. The total-to

2. Vavra, M. H., "Calculating Procedure of Sea-Level-Static Performance of Two-Spool Afterburning Bypass Jet Engine", Tech. Report NPS-57Va73061A, Naval Postgraduate School, Monterey, June 1973.

total stage efficiency is primarily a function of D_{RT} and the tip Mach number, although with small blade aspect ratios, as they occur in the later stages, the efficiency is also affected by tip clearance and end losses. These conditions will be taken into account in selecting appropriate values of the stage efficiencies, although it is not intended to support the chosen quantities by currently available loss evaluation methods which are at best approximate, and do not take into consideration the improvements that will be possible by future research efforts.

A calculating program for a Monroe 1880-22 programmable calculator has been set up to establish optimum solutions for particular design point conditions with minimum effort. The program consists of two parts. The first part (Program VA 511) calculates the compressor performance based on the tip conditions of the bladings, and determines the hub radii R_{h_1} and R_{h_3} of each stage for a specified hub/tip radius ratio of the first stage. These ratios are obtained by assuming that the axial velocity components V_{a1} and V_{a3} of Fig. 3 do not vary in the radial direction. It is assumed further that the flow through a stage has cylindrical stream surfaces and that along them the rotor has equal work input. Such conditions cannot exist in actuality because of the varying hub radii and because of curvature effects. It would also be more appropriate to design the rotors for equal total pressure ratios in radial direction than for equal work input. However, since this can be done only if the loss variation along the radius is known, the adopted method establishes only the general level of the work input per stage, without providing definite data for the design of the blading. To take account of the deterioration of the axial velocity profile in successive stages, a so-called work-done factor Ω is introduced, which is the ratio of the average work input for the actual velocity profile and that for a uniform velocity distribution. By introducing so-called blockage factors k, the reduction of the actual annulus flow area by the displacement thickness of the wall boundary layers is accounted for in an overall manner.

The diffusion factors of the rotor and stator bladings between hub and tip are calculated in the second part of the program (Program VA 512) for specified changes of the blade chords c_R and c_S of Fig. 2. These data together with the respective flow angles and Mach numbers of the absolute and relative velocities, which are determined also, establish criteria to judge whether the blading is acceptable for the chosen tip conditions.

The calculations are carried out with dimensionless quantities and for arbitrary fluids, which are supposed to have constant specific heats. Consistent units are used throughout to facilitate conversion to other systems of dimensions. For instance in the equation of state

$$\rho = \frac{p}{R_G\ T} \qquad (\mathrm{slug/ft^3}) \tag{2}$$

the gas constant R_G in the English system of units is

$$R_G = \frac{g(1545.43)}{M} = \frac{49{,}722.66}{M} \left(\frac{\text{ft-lb}}{\text{slug, }^{o}\text{R}} = \frac{\text{ft}^2}{\text{s}^2,\ ^{o}\text{R}} \right)$$

where M is the molecular weight of the gas. Further, the specific heat c_p equals

$$c_p = \frac{\gamma}{\gamma - 1} R_G \qquad \left(\frac{\text{ft-lb}}{\text{slug, }^{o}\text{R}} = \frac{\text{ft}^2}{\text{s}^2,\ ^{o}\text{R}} \right) \tag{3}$$

where $\gamma = c_p/c_v$. The velocity of sound a at the temperature T is then

$$a = \sqrt{\gamma\ R_G\ T} \qquad (\mathrm{ft/s}) \tag{4}$$

3. STAGE PERFORMANCE

If the velocity diagram of Fig. 3 pertains to the tip radius R_T of the blading of Fig. 1, the work input at the radius R_T is

$$\Delta H_T = U_T \left(\Delta W_u\right)_T \Omega = \omega R_T \left(\Delta W_u\right)_T \Omega \qquad \left(\frac{\text{ft-lb}}{\text{slug}}\right) \tag{5}$$

The subscript T is indicative of the tip conditions, Ω is the work-done factor, and ω the angular rotor velocity. At other radii $R = r R_T$, where $\Delta H = \Delta H_T$ by assumption,

$$\Delta H = \omega r R_T \left(\Delta W_u\right) \Omega = \Delta H_T$$

Hence, from Fig. 3 and with Eq. 5,

$$\omega R_T \left[V_{al} \tan \beta_{1T} - \lambda V_{al} \tan \beta_{2T}\right] = \omega R \left[V_{al} \tan \beta_1 - \lambda V_{al} \tan \beta_2\right]$$

or

$$\lambda \tan \beta_2 = \tan \beta_1 - \frac{1}{r}\left[\tan \beta_{1T} - \lambda \tan \beta_{2T}\right]$$

However, for constant axial velocity $V_1 = V_{al}$ along the radius of the blading ahead of the rotor,

$$\tan \beta_1 = \frac{U}{V_{al}} = r \frac{U_T}{V_{al}} = r \tan \beta_{1T} \tag{6}$$

and

$$\tan \beta_2 = \frac{1}{\lambda}\left(r - \frac{1}{r}\right) \tan \beta_{1T} + \frac{1}{r} \tan \beta_{2T} \tag{7}$$

From Eqs. A(2) and A(3) of Appendix A the angle β_{2T} is obtained for given angles β_{1T} and chosen values of λ, σ_{RT} and D_{RT}. With

$$X_T = \frac{\sin \beta_{1T} + 2 \sigma_{RT}\left(1 - D_{RT}\right)}{\lambda \cos \beta_{1T}} \tag{8}$$

there is

$$\sin \beta_{2T} = - \frac{2\sigma_{RT}}{X_T^2 + 1} + \sqrt{\frac{X_T^2 - 4 \sigma_{RT}^2}{X_T^2 + 1} + \left(\frac{2 \sigma_{RT}}{X_T^2 + 1}\right)^2} \tag{9}$$

The diffusion factor D_R at a radius $R = r R_T$ is, by Eq. A(1), with Eqs. 6 and 7

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{\frac{1}{r}\left(\tan \beta_{1T} - \lambda \tan \beta_{2T}\right)}{2\,\sigma_R} \cos \beta_1$$

From Eq. A(2) for the tip conditions

$$Y_T \equiv \tfrac{1}{2}\left(\tan \beta_{1T} - \lambda \tan \beta_{2T}\right) = \left(D_{RT} + \lambda \frac{\cos \beta_{1T}}{\cos \beta_{2T}} - 1\right) \frac{\sigma_{RT}}{\cos \beta_{1T}} \tag{10}$$

and

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{1}{r} \frac{\cos \beta_1}{\sigma_R} Y_T \tag{11}$$

The diffusion factor D_s of the stator blading is defined by

$$D_s = 1 - \frac{V_3}{V_2} + \frac{\Delta V_u}{2\,\sigma_s\, V_2}$$

or, by Fig. 3 and Eq. 1,

$$D_s = 1 - \lambda \cos \alpha_2 + \sin \alpha_2 \frac{1}{2\,\sigma_s} \tag{12}$$

Also

$$\tan \alpha_2 = \frac{\Delta V_u}{V_{a2}} = \frac{\Delta W_u}{\lambda V_{a1}} = \frac{V_{a1} \tan \beta_1 - \lambda V_{a1} \tan \beta_2}{\lambda V_{a1}}$$

With Eqs. 6, 7 and 10

$$\tan \alpha_2 = \frac{1}{r}\left(\frac{\tan \beta_{1T}}{\lambda} - \tan \beta_{2T}\right) = \frac{2\, Y_T}{\lambda\, r} \tag{13}$$

From this relation the angle α_2 is obtained at different radius ratios r which, introduced in Eq. 12, establishes the stator diffusion factor along the radius.

For a gas with c_p = constant, and for an adiabatic process, from Eq. 5 and Fig. 4

$$\Delta T_w = T_{t3} = T_{t1} = \frac{\Delta H_T}{c_p} = \frac{U_T\left(\Delta W_u\right)_T}{cp}\, \Omega = \frac{U_T^{\,2}}{cp}\; \frac{\left(\Delta W_u\right)_T}{U_T}\, \Omega$$

The total temperature T_{t1} at the inlet of the first stage is denoted by T_0

and the total pressure P_{t1} at this location is called P_0. Then

$$\frac{\Delta T_w}{T_0} = \frac{T_{t1}}{T_0}\left(\frac{T_{t3}}{T_{t1}} - 1\right) = \frac{U_T^{\,2}}{c_p\,T_0}\,\Omega\left(1 - \lambda\,\frac{\tan\,\beta_{2T}}{\tan\,\beta_{1T}}\right) \tag{14}$$

The dimensionless quantity $U_T/\sqrt{c_p\,T_0}$ is denoted by N_u, or, with Eq. 3,

$$N_u = \frac{U_T}{\sqrt{c_p\,T_0}} = \frac{U_T}{\sqrt{\frac{\gamma}{\gamma - 1}\,R_G\,T_0}} \tag{15}$$

Then

$$\frac{\Delta T_w}{T_0} = N_u^{\,2}\,\Omega\left(1 - \lambda\,\frac{\tan\,\beta_{2T}}{\tan\,\beta_{1T}}\right) \tag{16}$$

and

$$\frac{T_{t3}}{T_0} = \frac{T_{t1}}{T_0} + \frac{\Delta T_w}{T_0} \tag{17}$$

The stage efficiency η_S is defined as

$$\eta_S = \frac{\Delta T_{is}}{\Delta T_w}$$

where, according to Fig. 4, the quantity ΔT_{is} is the temperature difference $T'_{t3} - T_{t1}$, proportional to the work necessary to produce a pressure ratio P_{t3}/P_{t1} with an isentropic process. Thus

$$\frac{T'_{t3}}{T_{t1}} = \left(\frac{P_{t3}}{P_{t1}}\right)^{\frac{\gamma}{\gamma - 1}} = 1 + \frac{\Delta T_w}{T_{t1}}\,\eta_S = 1 + \frac{\Delta T_w}{T_0}\,\frac{1}{(T_{t1}/T_0)}\,\eta_S$$

Thus

$$\frac{P_{t3}}{P_{t1}} = \left(1 + \frac{\Delta T_w}{T_0}\,\frac{1}{(T_{t1}/T_0)}\,\eta_S\right)^{\frac{\gamma}{\gamma - 1}} \tag{18}$$

and

$$\frac{P_{t3}}{P_0} = \frac{P_{t3}}{P_{t1}} \frac{P_{t1}}{P_0} \tag{19}$$

4. CONDITIONS OF STATE IN STAGE

As shown in Fig. 4, the static temperature T_1 at station (1) ahead of the rotor is obtained from

$$T_1 = T_{t1} - \frac{V_1^2}{2\ cp} = T_{t1} - \frac{V_{a1}^2}{2\ cp} = T_{t1} - \frac{U_T^2 \cot^2 \beta_{1T}}{2\ cp}$$

T_1 is equal at all radii since V_{a1} is assumed to be constant at station (1). With Eq. 15

$$\frac{T_1}{T_{t1}} = 1 - \frac{N_u^2}{2} \frac{1}{T_{t1}/T_0} \cot^2 \beta_{1T} \tag{20}$$

or

$$\frac{T_1}{T_0} = T_{t1}/T_0 - \frac{N_u^2}{2} \cot^2 \beta_{1T} \tag{21}$$

The static pressure p_1 at station (1) is given by

$$\frac{p_1}{P_{t1}} = \left(\frac{T_1}{T_{t1}}\right)^{\frac{\gamma}{\gamma - 1}}$$

and

$$\frac{p_1}{P_0} = \frac{p_1}{P_{t1}} \frac{P_{t1}}{P_0} \tag{22}$$

The mass density $\rho_1 = p_1/(R_G\ T_1)$ is

$$\frac{\rho_1}{\rho_0} = \frac{p_1/P_0}{T_1/T_0} \tag{23}$$

where

$$\rho_0 = \frac{P_0}{R_G\ T_0} \tag{24}$$

By Fig. 4 and Eq. 1 the static temperature after the rotor is, with $T_{t2} = T_{t3}$,

$$T_2 = T_{t3} - \frac{V_2^{\,2}}{2\ cp} = T_{t3} - \frac{\lambda^2\ V_{a1}^{\,2}}{\cos^2\ \alpha_2}\ \frac{1}{2\ cp}$$

Also

$$\frac{T_2}{T_0} = \frac{T_{t3}}{T_0} - \frac{\lambda^2\ N_u^{\,2}\ \cot^2\ \beta_{1T}}{2\ \cos^2\ \alpha_2} \tag{25}$$

with T_{t3}/T_0 from Eq. 17. It must be noted that the angle α_2 changes along the radius. For different radius ratios r, the angle α_2 is obtained from Eq. 13.

Because only the overall stage efficiency η_S will be chosen, and not the rotor and stator efficiencies separately, the static pressure p_2, which varies along R also, cannot be determined with the present analysis. For this reason it is also not possible to evaluate the density ρ_2 at station (2).

From

$$T_3 = T_{t3} - \frac{V_3^{\,2}}{2\ cp} = T_{t3} - \frac{V_{a3}^{\,2}}{2\ cp}$$

in accordance with Fig. 4, and since by Eq. 1, $V_{a3} = \lambda^2\ V_{a1}$,

$$\frac{T_3}{T_{t3}} = 1 - \frac{\lambda^4\ N_u^{\,2}}{2}\ \frac{1}{(T_{t3}/T_0)}\ \cot^2\ \beta_{1T} \tag{26}$$

and

$$\frac{T_3}{T_0} = \frac{T_{t3}}{T_0} - \frac{\lambda^4\ N_u^{\,2}}{2}\ \cot^2\ \beta_{1T} \tag{27}$$

where T_{t3}/T_0 is known from Eq. 17. Because $V_3 = V_{a3}$ is assumed to be constant at station (3) the temperature T_3 is constant also, and the static pressure p_3 can be determined from

$$\frac{p_3}{P_{t3}} = \left(\frac{T_3}{T_{t3}}\right)^{\frac{\gamma}{\gamma - 1}} \tag{28}$$

or

$$\frac{p_3}{P_0} = \frac{p_3}{P_{t3}} \frac{P_{t3}}{P_0} \tag{29}$$

The mass density ρ_3 at station (3) is then, with Eq. 24,

$$\frac{\rho_3}{\rho_0} = \frac{p_3/P_0}{T_3/T_0} \tag{30}$$

5. HUB DIMENSIONS OF STAGE

The hub/tip ratio $r_1 = R_{h1}/R_T$ at station (1) of the first stage will be chosen, and is denoted by $(r_1)_I$. At this station there is $P_{t1} = P_0$ and $T_{t1} = T_0$. With a blockage factor $(k_1)_I$ the mass flow rate $\dot{m}$ is

$$\dot{m} = \pi R_T^2\left[1 - (r_1)_I^2\right] (V_{a1})_I (P_1)_I (k_1)_I \qquad \text{(slug/s)}$$

With Eq. 15, $V_{a1} = U_T \cot \beta_{1T}$, and Eqs. 24 and 22,

$$\dot{m} = \pi R_T^2\left[1 - (r_1)_I^2\right] N_u\sqrt{\frac{\gamma}{\gamma - 1} R_G T_0} \cot (\beta_{1T})_I\left[1 - \frac{N_u^2}{2} \cot^2(\beta_{1T})_I\right]^{\frac{1}{\gamma - 1}} \rho_0(k_1)_I$$

with ρ_0 from Eq. 24.

With the so-called referred dimensionless mass flow rate $\dot{m}_{REF}$

$$\dot{m}_{REF} \equiv \frac{\dot{m}\sqrt{\frac{\gamma - 1}{\gamma} R_G T_0}}{\pi R_T^2 P_0} = \frac{\dot{m}\left(\frac{\gamma - 1}{\gamma}\right)\sqrt{c_p T_0}}{\pi R_T^2 P_0} \tag{31}$$

there is also

$$\dot{m}_{REF} = \left[1 - (r_1)_I^2\right] N_u \cot (\beta_{1T})\left[1 - \frac{N_u^2}{2} \cot^2(\beta_{1T})_I\right]^{\frac{1}{\gamma - 1}} (k_1)_I \tag{32}$$

The angle $(\beta_{1T})_I$ is the relative inlet flow angle at the tip of the rotor of the first stage. Hence the quantity $\dot{m}_{REF}$ of Eq. 29 is determined by the chosen conditions at the inlet to the first stage.

At stations (1) of the other stages, there is

$$\dot{m} = \pi R_T^2 \left[1 - r_1^2\right] N_u \cot \beta_{1T} \frac{\rho_1}{\rho_0} \frac{P_0}{R_G T_0} k_1 \sqrt{\frac{\gamma}{\gamma - 1} R_G T_0} \tag{33}$$

or, with Eq. 31

$$r_1 = \left[1 - \frac{\dot{m}_{REF}/k_1}{N_u \cot \beta_{1T}(\rho_1/\rho_0)}\right]^{\frac{1}{2}} \tag{34}$$

The density ratio ρ_1/ρ_0 is known from Eq. 23.

At stations (3) of the stages, with $V_{a3} = \lambda^2 V_{a1}$ and the blockage factor k_3, the radius ratio $r_3 = R_{h3}/R_T$ is obtained from

$$r_3 = \left[1 - \frac{\dot{m}_{REF}/k_3}{\lambda^2 N_u \cot \beta_{1T}(\rho_3/\rho_0)}\right]^{\frac{1}{2}} \tag{35}$$

with ρ_3/ρ_0 from Eq. 30.

6. MACH NUMBERS OF STAGE VELOCITIES

At station (1) of a stage the velocity $V_1 = V_{a1}$ is constant. The relative velocities W_1 along the radius are

$$W_1 = \frac{V_1}{\cos \beta_1}$$

where β_1 for different radius ratios r is obtained from Eq. 6. Thus if the Mach number M_{V1} of the velocity V_1 is known there is

$$M_{W1} = \frac{W_1}{a_1} = \frac{V_1}{a_1} \frac{1}{\cos \beta_1} = M_{V1} \frac{1}{\cos \beta_1} \tag{36}$$

From Eqs. 4, 3, and 15 and $V_1 = U_T \cot \beta_{1T}$

$$M_{V1} = \frac{U_T \cot \beta_{1T}}{\sqrt{\gamma R_G T_1}} = \frac{N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\sqrt{T_1/T_0}} \tag{37}$$

The temperature ratio T_1/T_0 is given by Eq. 21.

At station (2) the absolute velocity V_2 varies along the radius, since $V_2 = V_{a2}/\cos \alpha_2$ with α_2 given by Eq. 13. Moreover $W_2 = V_{a2}/\cos \beta_2$, or

$$W_2 = V_2 \frac{\cos \alpha_2}{\cos \beta_2}$$

and the Mach number M_{W2} of W_2 is

$$M_{W2} = M_{V2} \frac{\cos \alpha_2}{\cos \beta_2} \tag{38}$$

The flow angle β_2 is obtained from Eq. 7 for different radius ratios r. There is

$$M_{V2} = \frac{V_{a2}}{\cos \alpha_2 \; a_2} = \frac{\lambda V_{a1}}{\cos \alpha_2 \; a_2} = \frac{\lambda U_T \cot \beta_{1T}}{\cos \alpha_2 \sqrt{\gamma R_G T_2}}$$

With Eq. 15

$$M_{V2} = \frac{\lambda N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\cos \alpha_2} \frac{1}{\sqrt{T_2/T_0}} \tag{39}$$

with T_2/T_0 from Eq. 25.

At station (3) the velocity V_3 and the temperature T_3 are constant. With $V_3 = \lambda^2 V_{a1}$ there is

$$M_{V3} = \frac{V_3}{a_3} = \frac{\lambda^2 N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\sqrt{T_3/T_0}} \tag{40}$$

where T_3/T_0 is known from Eq. 27.

7. STAGE-BY-STAGE CALCULATIONS (PROGRAM VA 511)

The following data have to be assumed for a particular design:

M = molecular weight of gas

γ = specific heat ratio of gas

$(\beta_{1T})_I$ = relative flow angle at tip of first-stage rotor

$(r_1)_I$ = hub/tip ratio at inlet of first-stage rotor

$(k_1)_I$ = blockage factor at inlet of first-stage

$N_u = U_T/\sqrt{c_p\ T_0}$ = dimensionless tip speed

The quantities listed below must be chosen for each stage J from J = I to J = J_{max}:

$(D_{RT})_J$ = diffusion factor at rotor tip

$(\sigma_{RT})_J$ = solidity at rotor tip

$\lambda_J = (V_{a2}/V_{a1})_J = (V_{a3}/V_{a2})_J$ = axial velocity ratio

Ω_J = work-done factor

$(\eta_S)_J$ = total-to-total stage efficiency

$(k_3)_J$ = blockage factor at stage exit

For J = I these values determine the referred mass flow rate $\dot{m}_{REF}$ of Eq. 32. With $(\beta_{1T})_I$, $(D_{RT})_I$, λ_I, the angle $(\beta_{2T})_I$ is obtained from Eqs. 8 and 9. Equations 16 and 17 establish $(T_{t3}/T_0)_I$ for $(T_{t1}/T_0)_I = 1$. The total pressure ratio $(P_{t3}/P_{t1})_I = (P_{t3}/P_0)_I$ is obtained from Eqs. 16 and 18. The density ratio $(\rho_3/\rho_0)_I$ can now be calculated from Eq. 30 to establish the ratio $(r_3)_I$ by means of Eq. 35.

For each stage from J = II to J_{max} the above-listed procedure must be carried out also, but the relative rotor tip angle $(\beta_{1T})_J$ must be determined from

$$(\tan\ \beta_{1T})_J = \frac{(\tan\ \beta_{1T})_{J\ -\ 1}}{(\lambda_{J\ -\ 1})^2} \tag{41}$$

Equation 41 is obtained because the axial velocity $V_3 = V_{a3}$ after a stage, which is V_{a1} of the next stage, equals $\lambda^2\ V_{a1}$ and since $\tan\ \beta_{1T} = U_T/V_{a1}$.

Moreover,

$$\left(\frac{T_{t1}}{T_0}\right)_J = \left(\frac{T_{t3}}{T_0}\right)_{J-1}$$

and

$$\left(\frac{P_{t1}}{P_0}\right)_J = \left(\frac{P_{t3}}{P_0}\right)_{J-1}$$

After the last stage J_{max} has been processed, the ratios

$$\left(\frac{P_{t3}}{P_0}\right)_{J_{max}} = \left(\frac{P_{t3}}{P_0}\right)_d \tag{42}$$

and

$$\left(\frac{T_{t3}}{T_0}\right)_{J_{max}} = \left(\frac{T_{t3}}{T_0}\right)_d \tag{43}$$

establish the overall total-to-total compressor efficiency η_c from

$$\eta_c = \frac{\left(P_{t3}/P_0\right)_d^{\frac{\gamma-1}{\gamma}} - 1}{\left(T_{t3}/T_0\right)_d - 1} \tag{44}$$

For a chosen tip radius R_T and values of T_0 and P_0 the mass flow rate of the compressor is from Eq. 31

$$\dot{m} = \dot{m}_{REF} \frac{\pi R_T^2 P_0}{\sqrt{\left(\frac{\gamma - 1}{\gamma}\right) R_G T_0}} \qquad \text{(slug/s)} \tag{45}$$

With R_T in inches, P_0 in psia, T_0 in $^{\circ}R$, and R_G in (ft-lb)/(slug, $^{\circ}R$), the flow rate is obtained in slug/s. Dividing $\dot{m}$ by $g = 32.174$ ft/s^2 gives the weight flow rate $\dot{w}$ in lbm/s.

The necessary driving power of the compressor in HP, exclusive of mechanical losses, equals

$$HP = \dot{m}\, c_p\, T_0 \left[\left(T_{t3}/T_0\right)_d - 1\right] \frac{1}{550} \tag{46}$$

From Eq. 15 the blade tip speed U_T is

$$U_T = N_u \sqrt{c_p\, T_0} \quad \text{(ft/s)}$$

and the rotative speed N of the compressor equals

$$N = \frac{U_T\, 360}{\pi\, R_T} \quad \text{(rpm)}$$

for R_T in inches.

The above-listed calculations can be performed with calculating program VA 511 on a programmable Monroe Calculator Model 1880-22. The operating instructions are given in Appendix B with a complete listing of the program steps. After a particular stage has been processed the stage data are printed by the calculator. These strips can be attached to Tables D-1 of Appendix B. After all stages have been calculated the overall compressor performance is printed. For easy identification, these paper strips can be attached to the lower half of Tables D-2 of Appendix D. Together with the print-outs at the start of the program, affixed to the upper portion of Table D-2, all pertinent overall compressor data are then listed in Table D-2 for particular configurations and assumptions.

After the printing of the individual stage data, these values must be written on one-half of a magnetic card (32 registers, starting at register 50) for use in program VA 512 to determine the particulars of the blading.

8. BLADING CALCULATIONS (PROGRAM VA 512)

This program handles each stage of the compressor separately. The data of a particular stage are transferred from program VA 511 to program VA 512 by means of magnetic cards.

The rotor blading is investigated first. These calculations are started by choosing the diffusion factor D_{Rh} at the hub at the rotor blading which is considered to be at the inner radius ratio r_1 at the rotor inlet. The diffusion factor D_{RT} is known from the preceding calculations. Then by Eq. A(1) of Appendix A the rotor blade solidity σ_{Rh} at r_1 is

$$\sigma_{Rh} = \frac{\tan \beta_{1h} - \lambda \tan \beta_{2h}}{2\left[\frac{\lambda}{\cos \beta_{2h}} - \frac{1 - D_{Rh}}{\cos \beta_{1h}}\right]} \tag{47}$$

The angles β_{1h} and β_{2h} are obtained from Eqs. 6 and 7, for $r = r_1$.

It will be assumed that the rotor blade chord varies linearly from c_{Rh} to c_{Rt} between r_1 and $r = 1$. Then at the radius ratios r between r_1 and unity,

$$c_R = c_{RT} - (c_{RT} - c_{Rh}) \frac{1 - r}{1 - r_1}$$

The balde spacing s_R is

$$s_R = s_{RT}\, r = s_{Rh} \frac{r}{r_1}$$

Thus the solidity σ_R at the radius ratio r equals

$$\sigma_R = \frac{1}{r}\left[\sigma_{RT} - (\sigma_{RT} - r_1\, \sigma_{Rh}) \frac{1 - r}{1 - r_1}\right] \tag{48}$$

The rotor blade diffusion factor D_R at the radius r can then be calculated by Eq. 11, with the angles β_1 and β_2 from Eqs. 6 and 7. These data are determined at two radius ratios between hub and tip, namely, at

$$r = r_1' = 1/3(1 + 2r_1) \tag{49}$$

and

$$r = r_1'' = 1/3(2 + r_1) \tag{50}$$

which correspond to stations at 1/3 and 2/3 of the blade height at the rotor inlet.

Equations 36 and 37 will be used to determine the Mach numbers of the relative velocities at the hub, tip and the intermediate radius ratios r_1'

and r_1''. Although the radius ratio r_2 at the hub after the rotor is larger than r_1, the flow angles and Mach numbers of the relative velocities W_2 after the rotor will be determined as if r_2 were equal to r_1; that is, at the radius ratios r_1, r_1', r_1'' and unity. These values are obtained with Eqs. 7, 13, 38, and 39.

The stator blading is treated as if the radius ratio r_2 were equal to r_3. The angle α_{2h} for $r = r_3$ is determined first with Eq. 12 for $r = r_3$. Then, a diffusion factor $D_S = D_{Sh}$ is chosen at $R_{3h} = r_3 R_T$, which establishes the solidity σ_{Sh} with Eq. 12 or from

$$\sigma_S = \frac{\sin \alpha_2}{2[\lambda \cos \alpha_2 - (1 - D_S)]} \qquad (51)$$

if $\alpha_2 = \alpha_{2h}$ and $D_S = D_{Sh}$. In the same manner the solidity σ_{ST} at the outer radius of the stator is established for a chosen diffusion factor D_{ST} at $r = 1$. Then at two radius ratios, namely,

$$r = r_3' = 1/3(1 + 2r_3)$$

and

$$r = r_3'' = 1/3(2 + r_3)$$

which are at 1/3 and 2/3 of the stator blade height, the solidity is obtained with a relation similar to Eq. 48, or

$$\sigma_S = \frac{1}{r}\left[\sigma_{ST} - (\sigma_{ST} - r_3 \, \sigma_{Sh}) \frac{1 - r}{1 - r_3}\right]$$

by assuming a liner change of the stator blade chord between hub and tip. The diffusion factor D_S at r can now be calculated by Eq. 12.

The data so established are used to determine the Mach numbers M_{V2} and M_{V3} of the absolute velocities ahead of and after the stator blades by means of Eqs. 39 and 40.

The operating instructions of program VA 512 are given in Appendix C, together with a listing of the calculating steps. Although the program can be loaded at any Branch Point, the Program Counts (P-Ct) of the operating instructions only hold for loading at Branch Point 00. At P-Ct 0014 the diffusion factor D_{Rh} of the rotor blading at the hub must be chosen. After the print-out of D_{Rh} and the corresponding calculated hub solidity σ_{Rh}, a decision must be made at P-Ct 0021 whether σ_{Rh} is acceptable for the selected tip solidity σ_{RT} of program VA 511. Entering "0" on the keyboard and depressing the (RESUME) key returns the program to P-Ct 0014 where an improved values of D_{Rh} can be introduced to obtain a better value of σ_{Rh}. This process can be repeated as often as necessary. If the best possible solidity σ_{Rh} has been obtained, the program exits the ($D_{Rh} \rightarrow \sigma_{Rh}$) loop if the (RESUME) key is depressed without entering "0" at P-Ct 0021. The last value of D_{Rh} which was introduced, and the corresponding solidity σ_{Rh} are then used to calculate and print the rotor blade data at the hub, the one-third and two-thirds blade heights, and at the tip. At the next stop of the program (P-Ct 0091), the paper tape can be removed and attached to the left-hand side of Table D-3 of Appendix D for ease of identification of the calculated values.

At the same P-Ct (0091), the diffusion factor D_{Sh} at the hub of the stator blade must be introduced before depressing the (RESUME) key. This value and the calculated hub solidity σ_{Sh} for D_{Sh} are printed out at P-Ct 0121. If the hub solidity σ_{Sh} has to be changed, the program can be returned to P-Ct 0091 by entering "0" on the keyboard and depressing the (RESUME) key. Depressing the (RESUME) key only, exits the program from the ($D_{Rh} \rightarrow \sigma_{Rh}$) loop, and stops the program at P-Ct 0131. At this stop a chosen value of the diffusion factor D_{ST} of the stator blading at the tip; that is, at the outer radius R_T, must be introduced before the (RESUME) key is depressed again. The chosen D_{ST} and the corresponding stator tip solidity σ_{ST} are printed out at P-Ct 0154. By entering "0" on the keyboard and depressing the (RESUME) key this value can be modified by introducing other quantities D_{ST} at P-Ct 0131. It is possible, however, that in view of the finally chosen hub diffusion factor D_{Sh} and/or the resulting blading hub solidity σ_{Sh} of the preceeding loop, the best possible solidity σ_{ST} obtained with the ($D_{ST} \rightarrow \sigma_{ST}$) loop does not produce an acceptable stator blading. In this case it is possible to jump from P-Ct 0154 to P-Ct 0099 by entering "-1" on the keyboard and depressing the (RESUME) key, to choose a more favorable hub diffusion factor D_{Sh} and a better solidity σ_{Sh} at the stator blade hub. If then the ($D_{ST} \rightarrow \sigma_{ST}$) loop produces an acceptable tip solidity σ_{ST} also, the (RESUME) key must be depressed at P-Ct 154 without entering either "0" or "-1" on the keyboard. During the following operation the calculator establishes and prints the stator blade data at the hub, the one-third and the two-thirds blade heights, and at the tip. The paper strip of this data can be removed at P-Ct 0208 and should be attached to the right-hand side of Table D-3 of Appendix D to identify the calculated numbers.

To process the blading data of another stage the keyboard instructions JUMP()(), 0, 0, (RESUME), must be entered at P-Ct 0208 to re-route the program to P-Ct 0003 where the magnetic card with the particulars of that stage must be read into the calculator.

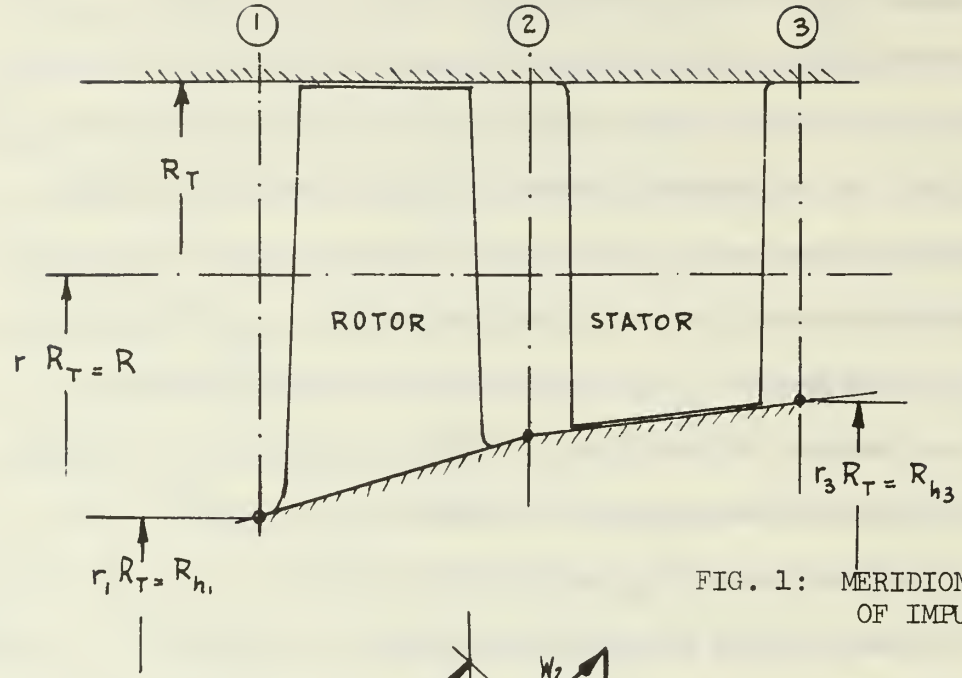

FIG. 1: MERIDIONAL CHANNEL
OF IMPULSE STAGE

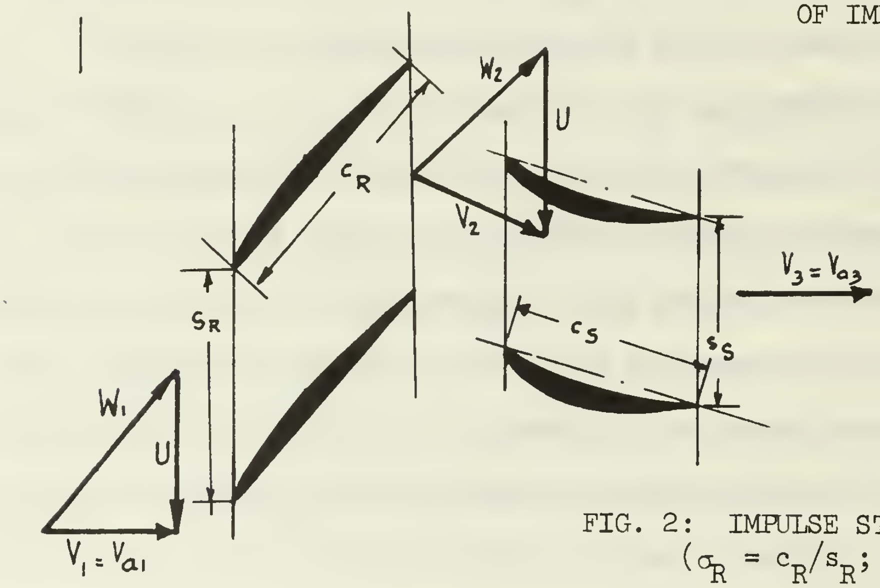

FIG. 2: IMPULSE STAGE BLADING
($\sigma_R = c_R/s_R$; $\sigma_S = c_S/s_S$)

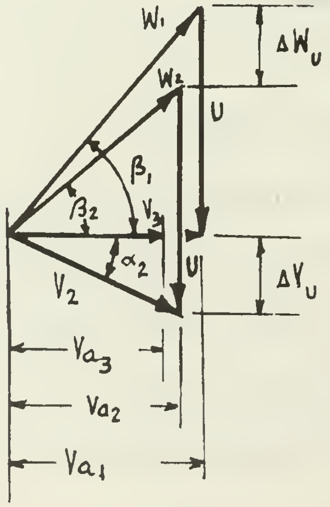

FIG. 3: VELOCITY DIAGRAM
OF IMPULSE BLADING

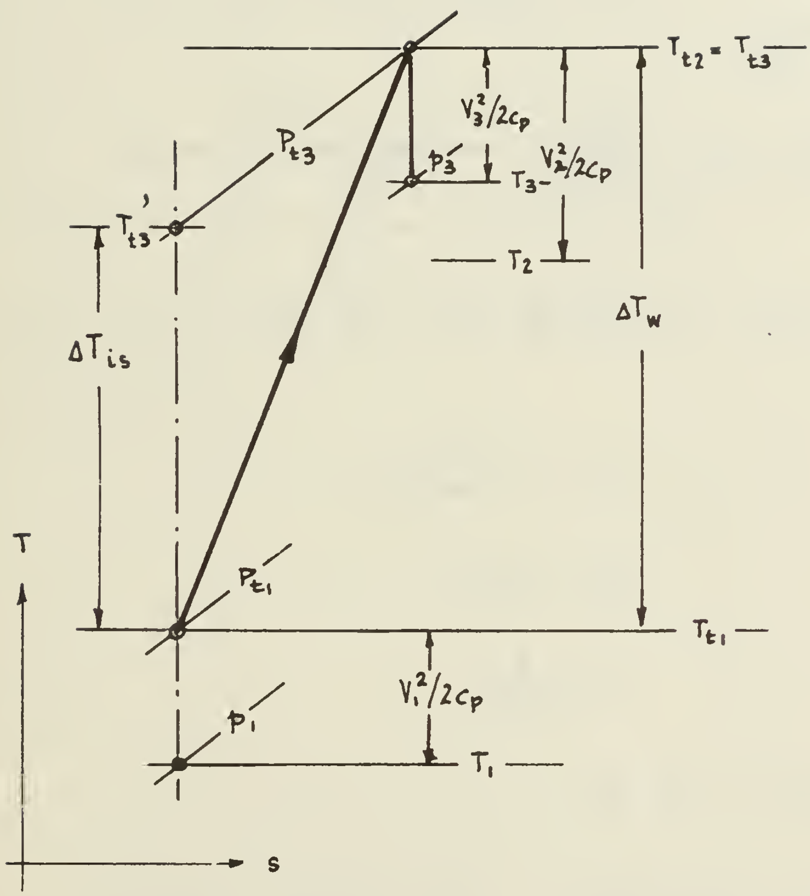

FIG. 4: COMPRESSION PROCESS OF STAGE IN ENTROPY DIAGRAM

T_t = Total Temperature

T = Static Temperature

P_t = Total Pressure

p = Static Pressure

APPENDIX A: FLOW DEFLECTION FOR GIVEN INLET ANGLE SPECIFIED DIFFUSION FACTOR, AND AXIAL VELOCITY RATIO

With they symbols of Fig. 1 the rotor diffusion factor D_R is defined by

$$D_R = 1 - \frac{W_2}{W_1} + \frac{\Delta W_u}{2\ \sigma_R\ W_1}$$

With $V_{a2} = \lambda\ V_{a1}$

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{\tan \beta_1 - \lambda \tan \beta_2}{2\ \sigma_R} \cos \beta_1 \qquad A(1)$$

Rewritten

$$A \cos \beta_2 = B + C \sin \beta_2$$

where

$$A = 1 + \frac{\sin \beta_1}{2\ \sigma_R} - D_R$$

$$B = \lambda \cos \beta_1$$

$$C = \frac{B}{2\ \sigma_R}$$

With $\cos^2 \beta_2 = 1 - \sin^2 \beta_2$,

$$A^2(1 - \sin^2 \beta_2) = B^2 + 2BC \sin \beta_2 + C^2 \sin^2 \beta_2$$

and

$$\sin \beta_2 = - \frac{BC}{A^2 + C^2} \overset{+}{(-)} \sqrt{\frac{A^2 - B^2}{A^2 + C^2} + \left(\frac{BC}{A^2 + C^2}\right)^2}$$

There are:

$$\frac{BC}{A^2 + C^2} = \frac{B^2}{2\ \sigma_R} \frac{1}{A^2 + \frac{B^2}{4\ \sigma_R}} = \frac{2\ \sigma_R}{4\ \sigma_R{}^2 \left(\frac{A}{B}\right)^2 + 1}$$

$$\frac{A^2 - B^2}{A^2 + C^2} = \frac{\left(\frac{A}{B}\right)^2 - 1}{\left(\frac{A}{B}\right)^2 + \frac{1}{4\ \sigma_R^{\ 2}}} = \frac{4\ \sigma_R^{\ 2}\left(\frac{A}{B}\right)^2 - 4\ \sigma_R^{\ 2}}{4\ \sigma_R^{\ 2}\left(\frac{A}{B}\right)^2 + 1}$$

Let

$$X = 2\ \sigma_R \frac{A}{B} = \frac{\sin\ \beta_1 + 2\ \sigma_R(1 - D_R)}{\lambda \cos\ \beta_1} \qquad A(2)$$

Then

$$\sin\ \beta_2 = -\frac{2\ \sigma_R}{X^2 + 1} + \sqrt{\frac{X^2 - 4\ \sigma_R^{\ 2}}{X^2 + 1} + \left(\frac{2\ \sigma_R}{X^2 + 1}\right)^2} \qquad A(3)$$

Hence for known values of β_1, σ_R, λ, and D_R the flow angle β_2 is obtained from Eqs. A(2) and A(3).

APPENDIX B: PROGRAM VA 511 FOR MONROE 1880-22 PROGRAMMABLE CALCULATOR

STAGE-BY-STAGE CALCULATIONS AND OVER-ALL PERFORMANCE OF MULTI-STAGE AXIAL COMPRESSOR WITH IMPULSE BLADINGS

OPERATING INSTRUCTIONS PROGRAM VA 511 (MONROE 1880-22 CALCULATOR)

MULTI-STAGE AXIAL COMPRESSOR WITH IMPULSE BLADING
(Set-Up: LOAD MAGNETIC CARDS OF PROGRAM AT BRANCH PT. 00; D.P. 4)

P-COUNT	ENTER		PRINT-OUT
0010	M		M
0017	γ		γ
0051	β_{1T}	First Stage	β_{1T}
0064	r_1	First Stage	r_1
0072	k_1	First Stage	k_1
0091	$N_u = \dfrac{U_T}{\sqrt{c_p\ T_0}}$		N_u
0206	D_{RT}	Stage J(J = 1 to J = J_{max}	$\dot{m}_{REF}$
0211	σ_{RT}	Stage J(J = 1 to J = J_{max}	
0221	λ	Stage J(J = 1 to J = J_{max}	
0290	Ω	Stage J(J = 1 to J = J_{max}	
0320	η_s	Stage J(J = 1 to J = J_{max}	
0425	k_3	Stage J(J = 1 to J = J_{max}	
0585	WRITE Stage Data on one side of Magnetic card with set-up: [↑()()] 50, WRITE		Data Stage J (see Table D-1)

$(J + 1) \leqq J_{max}$ (RESUME) — return to P-count 0206

$(J + 1) > J_{max}$ ENTER: 0 (RESUME)

P-COUNT	ENTER	PRINT-OUT
0670	ENTER: T_0 (^oR)	
0678	" : P_0 (psia)	
0688	" : $D_T = 2\ R_T$ (inches)	Compressor Data (see Table D-2)
0838	HALT	

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
00		4				
01		9				
02		7				
03		2				
04		2				
05		.				
06		6				
07		6	$\mathcal{R}$			
08		÷				
09		HALT	M	M		
10		PRINT x				M
11		x	R_G			
12		↓( )( )				
13		0				
14		0			$R_G \rightarrow 00$	
15		(				
16		HALT	γ	γ		
17		↓( )( )				
18		0				
19		1			$\gamma \rightarrow 01$	
20		PRINT X				γ
21		÷				
22		(				
23		↑( )( )				
24		0				
25		1	γ			
26		−				
27		1				
28		)	$\gamma-1$			
29		↓( )( )				
30		0				
31		2			$\gamma-1 \rightarrow 02$	
32		)	$\gamma/(\gamma-1)$			
33		↓( )( )				
34		0				
35		3			$\frac{\gamma}{\gamma-1} \rightarrow 03$	
36		=	c_p			
37		↓( )( )				
38		0				
39		4			$c_p \rightarrow 04$	
40		↑( )( )				
41		0				
42		2	$\gamma-1$			
43		INV	$\frac{1}{\gamma-1}$			
44		↓( )( )				
45		0				
46		5			$\frac{1}{\gamma-1} \rightarrow 05$	
47	ECODE	176	PRINT LINE OF DOTS			
48		SET D.P				
49		4				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
5	0		HALT	$(\beta_{1T})_I$	$(\beta_{1T})_I$		
	1		↓( )( )				
	2		8			$(\beta_{1T})_I \rightarrow 80$	
	3		0				
	4		PRINT X				$(\beta_{1T})_I$
	5	ECODE	073	$\tan(\beta_{1T})_I$			
	6		INV	$\cot(\beta_{1T})_I$			
	7		↓( )( )				
	8		0				
	9		8			$\cot(\beta_{1T})_I \rightarrow 08$	
6	0		1	1			
	1		−				
	2		(				
	3		HALT	$(r_1)_I$	$(r_1)_I$		
	4		↓( )( )				
	5		5				
	6		1			$(r_1)_I \rightarrow 51$	
	7		PRINT X				$(r_1)_I$
	8		X				
	9		)	$(r_1)_I^2$			
7	0		×	$1-(r_1)_I^2$			
	1		HALT		$(k_1)_I$		
	2		PRINT X				$(k_1)_I$
	3		↓( )( )				
	4		5				
	5		7			$(k_1)_I \rightarrow 57$	
	6		×				
	7		↑( )( )				
	8		0				
	9		8	$\cot(\beta_{1T})_I$			
8	0		=	$b = (k_1)_I[1-(r_1)_I^2]\cot(\beta_{1I})$			
	1		↓( )				
	2		0			$b \rightarrow 0$	
	3	ECODE	176	PRINT LINE OF DOTS			
	4		↑( )( )				
	5		5				
	6		1	$(r_1)_I$			
	7		↓( )				
	8		7			$(r_1)_I \rightarrow 7$	
	9						
9	0		HALT	N_u	N_u		
	1		↓( )( )				
	2		1				
	3		0			$N_u \rightarrow 10$	
	4		PRINT X				N_u
	5		×				
	6		↑( )( )				
	7		0				
	8		8	$\cot(\beta_{1T})_I$			
	9		×				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
100		÷				
1		2				
2		CHSGN				
3		+				
4		1				
5		a^x	$(T_1/T_0)_I = 1 - \frac{Nu^2}{2}\cot^2(\beta_{1T})_I$			
6		↓( )( )				
7		6				
8		2			$(T_1/T_0)_I \rightarrow 62$	
9		↑( )( )				
110		0				
1		3	$\frac{\gamma}{\gamma-1}$			
2		÷	$(p_1/P_0)_I$			
3		↓( )( )				
4		6				
5		3			$(p_1/P_0)_I \rightarrow 63$	
6		↑( )( )				
7		6				
8		2	$(T_1/T_0)_I$			
9		x				
120		↑( )				
1		0	b			
2		x				
3		↑( )( )				
4		1				
5		0	Nu			
6		=	$\dot{m}_{REF}$			
7		↓( )( )				
8		1				
9		1			$\dot{m}_{REF} \rightarrow 11$	
130		PRINT A				$\dot{m}_{REF}$
1	E CODE	176	PRINT 2 LINES OF DOTS			
2	E CODE	176				
3		1	1			
4		↓( )( )				
5		8				
6		1	$(\lambda)_{J-1}$ for J = 1 = 1		1 → 81	
7		↓( )( )				
8		6				
9		0	$(T_{t1}/T_0)_I = 1$		1 → 60	
140		↓( )( )				
1		6				
2		1	$(P_{t1}/P_0)_I = 1$		1 → 61	
3		↑( )( )				
4		0				
5		3	$\gamma/(\gamma-1)$			
6		INV	$(\gamma-1)/\gamma$			
7		↓( )( )				
8		0				
9		6			$\frac{\gamma-1}{\gamma} \rightarrow 06$	

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
150 0		↑( )( )				
1		0				
2		8	$\cot(\beta_{1T})_I$			
3		INV	$\tan(\beta_{1T})_I$			
4		↓( )( )				
5		7				
6		7			$\tan(\beta_{1T})_I \rightarrow 77$	
7		0				
8		↓( )				
9		6	SETS PRINTG. IDENTIFIER TO ZERO			
160 0		↑( )( )	START OF STAGE BY STAGE CALC.			
1		7				
2		7	$\tan(\beta_{1T})_{J-1}$			
3		÷				
4		(				
5		↑( )( )				
6		8				
7		1	$(\lambda)_{J-1}$			
8		×				
9		)	$(\lambda)^2_{J-1}$			
170 0		=	$\tan(\beta_{1T})_J$			
1		↓( )( )				
2		7				
3		7			$\tan(\beta_{1T})_J \rightarrow 77$	
4		INV	$\cot(\beta_{1T})_J$			
5		×				
6		↑( )( )				
7		1				
8		0	N_u			
9		÷	$N_u \cot(\beta_{1T})_J$			
180 0		(				
1		↑( )( )				
2		0				
3		2	$\gamma - 1$			
4		a^x				
5		.				
6		5				
7		)	$\sqrt{\gamma-1}$			
8		=	$(N_{u1})_J = (N_u/\sqrt{\gamma-1}) \cot(\beta_{1T})_J$			
9		↓( )( )				
190 0		7				
1		6			$(N_{u1})_J \rightarrow 76$	
2		↑( )( )				
3		7				
4		7	$\tan(\beta_{1T})_J$			
5	E CODE	103	$(\beta_{1T})_J$ RAD			
6		R→°	$(\beta_{1T})_J{}^\circ$			
7		↓( )( )				
8		5				
9		0			$(\beta_{1T})_J \rightarrow 50$	

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
20	0		SIN/COS	$\sin(\beta_{IT})_J$			
	1		+				
	2		(				
	3		1	1			
	4		−				
	5		HALT	$(D_{RT})_J$	$(D_{RT})_J$		
	6		↓( )( )				
	7		5				
	8		2			$(D_{RT})_J \to 52$	
	9		×				
21	0		HALT	$(\sigma_{RT})_J$	$(\sigma_{RT})_J$		
	1		↓( )( )				
	2		5				
	3		3			$(\sigma_{rT})_J \to 53$	
	4		×				
	5		2				
	6		)				
	7		÷				
	8		2NDFUNC	$\cos(\beta_{IT})_J$			
	9		÷				
22	0		HALT	λ_J	λ_J		
	1		↓( )( )				
	2		5				
	3		4			$\lambda_J \to 54$	
	4		×	$(X_T)_J$			
	5		+	$(X_T)_J^2$			
	6		↓( )				
	7		1			$(X_{TJ})^2 \to 1$	
	8		1	1			
	9		=	$(X_T)_J^2+1$			
23	0		↓( )				
	1		2			$1+X_T^2 \to 2$	
	2		↑( )( )				
	3		5				
	4		3	$(\sigma_{RT})_J$			
	5		×				
	6		2				
	7		÷	$2(\sigma_{rT})_J$			
	8		↑( )				
	9		2	X_T^2+1			
24	0		×	$2\sigma_{RT}/(X_T^2+1)$			
	1		↓( )				
	2		3			$2\sigma_{rT}/(X_T^2+1) \to 3$	
	3		+	$(2\sigma_{RT}/(X_T^2+1))^2$			
	4		(				
	5		↑( )				
	6		1	X_T^2			
	7		−				
	8		(				
	9		2				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
250		x				
1		↑( )( )				
× 2		0				
3		3	(σ_{RT})			
4		x	$2(\sigma_{RT})$			
5		)	$4(\sigma_{RT})^2$			
6		÷	$X_T^2 - 4(\sigma_{RT})^2$			
7		↑( )				
8		2	$X_T^2 + 1$			
9		)	$(X_T^2 - 4(\sigma_{RT})^2)/(X_T^2+1)$			
260		=				
1		$\sqrt{}$				
2		−				
3		↑( )				
4		3	$2\sigma_{RT}/(X^2+1)$			
5		=	$\sin(\beta_{2T})_J$			
6		$\sin^{-1}/\cos^{-1}$	$(\beta_{2T})_J^R$			
7		R→°	$(\beta_{2T})_J^\circ$			
8		↓( )( )				
9		5				
270		9			$(\beta_{2T})_J \rightarrow 59$	
1	ECODE	073	$\tan(\beta_{2T})_J$			
2		↓( )( )				
3		7				
4		8			$\tan(\beta_{2T})_J \rightarrow 78$	
5		÷				
6		↑( )( )				
7		7				
8		7	$\tan(\beta_{1T})_J$			
9		x				
280		↑( )( )				
1		5				
2		4	$(\lambda)_J$			
3		CHSGN				
4		+	$-\lambda\tan\beta_{2T}/\tan\beta_{1T}$			
5		1				
6		x	$1-(\lambda\tan\beta_{2T}/\tan\beta_{1T})$			
7		↓( )				
8		4			$1-(\lambda\tan\beta_2/\tan\beta_1)\rightarrow 4$	
9		HALT	Ω_J	Ω_J		
290		↓( )( )				
1		5				
2		5			$\Omega_J \rightarrow 55$	
3		x				
4		(				
5		↑( )( )				
6		1				
7		0	Nu			
8		x				
9		)	Nu^2			

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
300		+	$(\Delta T_W/T_0)_J$			
1		↓( )( )				
2		6				
3		5			$\left(\frac{\Delta T_W}{T_0}\right)_J \rightarrow 65$	
4		↑( )( )				
5		6				
6		0	$(T_{t1}/T_0)_J$			
7		=	$(T_{t3}/T_0)_J$			
8		↓( )( )				
9		6				
310		6			$\left(\frac{T_{t3}}{T_0}\right)_J \rightarrow 66$	
1		↑( )( )				
2		6				
3		5	$(\Delta T_W/T_0)_J$			
4		÷				
5		↑( )( )				
6		6				
7		0	$(T_{t1}/T_0)_J$			
8		×				
9		HALT	$(\eta_s)_J$	$(\eta_s)_J$		
320		↓( )( )				
1		5				
2		6			$(\eta_s)_J \rightarrow 56$	
3		+				
4		1				
5		a^x	T_{t3}'/T_{t1}			
6		↑( )( )				
7		0				
8		3	$\gamma/(\gamma-1)$			
9		×	$(P_{t3}/P_t)_J$			
330		↑( )( )				
1		6				
2		1	$(P_{t1}/P_0)_J$			
3		=	$(P_{t3}/P_0)_J$			
4		↓( )( )				
5		6				
6		9			$(P_{t3}/P_0)_J \rightarrow 69$	
7		↑( )( )				
8		1				
9		0	N_u			
340		÷				
1		↑( )( )				
2		7				
3		7	$\tan(\beta_{1T})_J$			
4		×	$N_u/\tan(\beta_{1T})_J$			
5		÷	$[N_u/\tan(\beta_{1T})_J]^2$			
6		2				
7		÷	$[N_u \cot(\beta_{1T})_J]^2/2 = Z_J$			
8		↓( )( )				
9		7				

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
35	0		5			$Z_J \rightarrow 75$	
	1		↑( )( )				
	2		6				
	3		0	$(T_{t1}/T_0)_J$			
	4		CHSGN				
	5		+				
	6		1				
	7		a^x	$1 - Z_J/(T_{t1}/T_0)_J = T_1/T_{t1}$			
	8		↑( )( )				
	9		0				
36	0		3	$\gamma/(\gamma-1)$			
	1		x	$(p_1/P_{t1})_J$			
	2		↑( )( )				
	3		6				
	4		1	$(P_{t1}/P_0)_J$			
	5		=	$(p_1/P_0)_J$			
	6		↓( )( )				
	7		6				
	8		3			$(p_1/P_0)_J \rightarrow 63$	
	9		↑( )( )				
37	0		6				
	1		0	$(T_{t1}/T_0)_J$			
	2		−				
	3		↑( )( )				
	4		7				
	5		5	Z_J			
	6		=	$(T_1/T_0)_J$			
	7		↓( )( )				
	8		6				
	9		2			$(T_1/T_0)_J \rightarrow 62$	
38	0		↑( )( )				
	1		5				
	2		4	λ			
	3		a^x				
	4		4				
	5		x	λ^4			
	6		↑( )( )				
	7		7				
	8		5	Z_J			
	9		CHSGN				
39	0		+	$-\lambda^4 Z_J$			
	1		↓( )				
	2		5			$-\lambda^4 Z_J \rightarrow 5$	
	3		1	1			
	4		a^x	$1 - \lambda^4 Z_J = (T_3/T_{t3})$			
	5		↑( )( )				
	6		0				
	7		3	$\gamma/(\gamma-1)$			
	8		x	(p_3/P_{t3})			
	9		↑( )( )				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
400		6				
1		9	$(P_{t3}/P_0)_J$			
2		=	$(p_3/P_0)_J$			
3		↓( )( )				
4		7				
5		2			$(p_3/P_0)_J \rightarrow 72$	
6		↑( )( )				
7		6				
8		6	$(T_{t3}/T_0)_J$			
9		+				
410		↑( )				
1		5	$-\lambda^4(N_u^2/2)\cot^2(\beta_{1J})$			
2		÷	$(T_3/T_0)_J$			
3		↓( )( )				
4		7				
5		1			$(T_3/T_0)_J \rightarrow 71$	
6		↑( )( )				
7		7				
8		2	$(p_3/P_0)_J$			
9		×	(ρ_0/ρ_3)			
420		↑( )( )				
1		1				
2		1	$\dot{m}_{REF}$			
3		÷	$\dot{m}_{REF}(\rho_0/\rho_3)$			
4		HALT		$(K_3)_J$		
5		↓( )( )				
6		5				
7		8			$(K_3)_J \rightarrow 58$	
8		÷	$(\dot{m}_{REF}/K_3)(\rho_0/\rho_3$			
9		(				
430		↑( )( )				
1		5				
2		4	λ_J			
3		×				
4		)	λ_J^2			
5		÷				
6		↑( )( )				
7		1				
8		0	N_u			
9		×				
440		↑( )( )				
1		7				
2		7	$\tan(\beta_{1T})_J$			
3		CHSGN				
4		+				
5		1				
6		=				
7		$\sqrt{}$	r_3			
8		↓( )( )				
9		7				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
450		3			$(r_3)_J \to 73$	
1		↑( )				
2		4	$1-\left(\lambda \frac{\tan\beta_{2T}}{\tan\beta_{1T}}\right)_J$			
3		x				
4		↑( )( )				
5		7				
6		7	$(\tan\beta_{1T})_J$			
7		÷				
8		2				
9		=	$(\gamma_T)_J$			
460		↓( )( )				
1		7				
2		9			$(\gamma_T)_J \to 79$	
3		↑( )( )				
4		5				
5		0	$(\beta_{1T})_J$			
6		−				
7		↑( )( )				
8		5				
9		9	$(\beta_{2T})_J$			
470		=	$\beta_{1T}-\beta_{2T} = \Delta\beta_T$			
1		↓( )( )				
2		6				
3		7			$\Delta\beta_T \to 67$	
4		0				
5		0				
6		0	FILLER			
7		0				
8		0				
9		0				
480		↑( )( )	$(\beta_{1T})_J$			
1		5				
2		0				
3		1				
4		.	PRINTING IDENTIFIER			
5		0	INCREMENT			
6		0				
7		0				
8		0				
9		↓( )				
490		+				
1		6				
2		↑( )				
3		6	CHANGE OF PRINTG. IDENTIFIER			
4	ECOBE	177				
5		PRINTA				$(\beta_T)_J$
6		↑( )( )				
7		5				
8		2	$(D_{RT})_J$			
9		PRINTA				$(D_{RT})_J$

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
500		↑( )( )				
1		5				
2		3	$(\sigma_{RT})_J$			
3		PRINT A				$(\sigma_{RT})_J$
4		↑( )( )				
5		5				
6		4	λ_J			
7		PRINT A				λ_J
8		↑( )( )				
9		5				
510		9	$(\beta_{2T})_J$			
1		PRINT A				$(\beta_{2T})_J$
2		↑( )( )				
3		6				
4		7	$(\Delta\beta_T)_J$			
5		PRINT A				$(\Delta\beta_T)_J$
6	ECODE	065	PAPER ADVANCE			
7		↑( )( )				
8		5				
9		5	Ω_J			Ω_J
520		PRINT A				
1		↑( )( )				
2		5				
3		6	$(\eta_s)_J$			
4		PRINT A				$(\eta_s)_J$
5	ECODE	176	PRINT LINE OF DOTS			
6		↑( )( )				
7		6				
8		0	$(T_{t1}/T_0)_J$			
9		PRINT A				$(T_{t1}/T_0)_J$
530		↑( )( )				
1		6				
2		1	$(P_{t1}/P_0)_J$			
3		PRINT A				$(P_{t1}/P_0)_J$
4	ECODE	065	PAPER ADVANCE			
5		↑( )( )				
6		6				
7		2	$(T_1/T_0)_J$			
8		PRINT A				$(T_1/T_0)_J$
9		↑( )( )				
540		6				
1		3	$(p_1/P_0)_J$			
2		PRINT A				$(p_1/P_0)_J$
3	ECODE	176				
4	ECODE	176	2 LINES OF DOTS			
5		↑( )( )				
6		6				
7		6	$(T_{t3}/T_0)_J$			
8		PRINT A				$\left(\frac{T_{t3}}{T_0}\right)_J$
9		0	FILLER			

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
550		↑( )( )				
1		6				
2		9	$(P_{t3}/P_0)_J$			
3		PRINT A				$(P_{t3}/P_0)_J$
4	ECODE	065	PAPER ADVANCE			
5		↑( )( )				
6		7				
7		1	$(T_3/T_0)_J$			
8		PRINT A				$(T_3/T_0)_J$
9		↑( )( )				
560		7				
1		2	$(P_3/P_0)_J$			
2		PRINT A				$(P_3/P_0)_J$
3	ECODE	176				
4	ECODE	176				
5	ECODE	176	3 LINES OF DOTS			
6		↑( )( )				
7		5				
8		1	$(r_1)_J$			
9		PRINT A				$(r_1)_J$
570		↑( )( )				
1		5				
2		7	$(k_1)_J$			$(k_1)_J$
3		PRINT A				
4	ECODE	065	PAPER ADVANCE			
5		↑( )( )				
6		7				
7		3	$(r_3)_J$			
8		PRINT A				$(r_3)_J$
9		↑( )( )				
580		5				
1		8	$(k_3)_J$			
2		PRINT A				$(k_3)_J$
3	ECODE	176	1 LINE OF DOTS			
4		HALT	READ REGISTERS 50-81 ON MAG. CARD			
5		BRANCH	ENTER 0 IF ALL STAGES HAVE BEEN PROCESSED			
6		=				
7		6				
8		4	GO TO BP 64 IF ALL STAGES HAVE BEEN PROCESSED			
9		↑( )( )				
590		5				
1		0	$(\beta_{1T})_{J-1}$			
2		↓( )( )				
3		8	SETTING-UP OF INLET			
4		0	CONDITIONS OF NEXT		$(\beta_{1T})_{J-1} \to 80$	
5		↑( )( )	STAGE			
6		5				
7		4	$(\lambda)_{J-1}$			
8		↓( )( )				
9		8				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
600		1			$\lambda_{J-1} \rightarrow 81$	
1		↑( )( )				
2		7				
3		3	$(r_3)_{J-1}$			
4		↓( )( )				
5		5				
6		1	$(r_1)_J$		$(r_1)_J \rightarrow 51$	
7		↑( )( )				
8		7				
9		3	$(K_3)_{J-1}$			
610		↓( )( )				
1		5				
2		7	$(K_1)_J$		$(K_1)_J \rightarrow 57$	
3		↑( )( )				
4		6				
5		6	$(T_{t3}/T_0)_{J-1}$			
6		↓( )( )				
7		6				
8		0	$(T_{t1}/T_0)_J$		$\left(\frac{T_{t1}}{T_0}\right)_J \rightarrow 60$	
9		↑( )( )				
620		6				
1		9	$(P_{t3}/P_0)_{J-1}$			
2		↓( )( )				
3		6				
4		1	$(P_{t1}/P_0)_J$		$\left(\frac{P_{t1}}{P_0}\right)_J \rightarrow 61$	
5		↑( )( )				
6		7				
7		1	$(T_3/T_0)_{J-1}$			
8		↓( )( )				
9		6				
630		2	$(T_1/T_0)_J$		$(T_1/T_0)_J \rightarrow 62$	
1		↑( )( )				
2		7				
3		2	$(p_3/p_0)_{J-1}$			
4		↓( )( )				
5		6				
6		3	$(p_1/p_0)_J$		$\left(\frac{p_1}{p_0}\right)_J \rightarrow 63$	
7		JUMP				
8		1				
9		6	TO BPT 16 FOR NEW STAGE			
640		↑( )( )				
1		6				
2		9	$(P_{t3}/P_0)_d$			
3		a^x				
4		↑( )( )				
5		0				
6		6	$(\gamma-1)/\gamma$			
7		−				
8		1				
9		÷				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
650		(				
1		↑( )( )				
2		6				
3		6	$(T_{t3}/T_0)_d$			
4		−				
5		1				
6		)				
7		=	η_c			
8		↓( )( )				
9		1				
660		2			$\eta_c \rightarrow 12$	
1		↑( )( )				
2		0				
3		6	$(\gamma-1)/\gamma$			
4		×				
5		↑( )( )				
6		0				
7		0	R_G			
8		×				
9		HALT	T_0	T_0		
670		↓( )( )				
1		1				
2		3			$T_0 \rightarrow 13$	
3		=				
4		√	$\sqrt{\frac{\gamma-1}{\gamma} R_G T_0}$			
5		INV				
6		×				
7		HALT	P_0	P_0		
8		↓( )( )				
9		1				
680		4			$P_0 \rightarrow 14$	
1		×				
2		π				
3		÷				
4		4				
5		×				
6		(				
7		HALT	D_T	$D_T = 2R_T$		
8		↓( )( )				
9		1				
690		5			$D_T \rightarrow 15$	
1		×				
2		)				
3		×				
4		↑( )( )				
5		1				
6		1	$\dot{m}_{REF}$			
7		×				
8		↓( )( )				
9		1				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
700		6			$\dot{m} \rightarrow 16$	
1		3				
2		2				
3		•				
4		1				
5		7				
6		4	g			
7		=	$\dot{w}$ (lbm/s)			
8		↓( )( )				
9		1				
710		7				
1		↑( )( )				
2		6				
3		6	$(T_{t3}/T_0)d$			
4		−				
5		1				
6		×	$(T_{t3}/T_0)d - 1$			
7		↑( )( )				
8		1				
9		3	T_0			
720		×				
1		↑( )( )				
2		0				
3		4	C_p			
4		×				
5		↑( )( )				
6		1				
7		6	$\dot{m}$			
8		÷				
9		5				
730		5				
1		0				
2		=	HP			
3		↓( )( )				
4		×				
5		8			HP → 18	
6	E CODE	176	1 LINE OF DOTS			
7		↑( )( )				
8		1				
9		4	P_0 (psia)			
740		PRINT A				P_0
1		↑( )( )				
2		1				
3		3	T_0 (°R)			
4		PRINT A				T_0
5		↑( )( )				
6		1				
7		5	D_T (in.)			
8		PRINT A				D_T
9	E CODE	065	PAPER ADVANCE			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
75	0		↑( )( )				
	1		6				
	2		9	$(P_{t3}/P_0)_d$			
	3		PRINT A				$\left(\frac{P_{t3}}{P_0}\right)_d$
	4		↑( )( )				
	5		1				
	6		2	η_c			
	7		x				
	8		1				
	9		0				
76	0		0				
	1		=	η_c (%			
	2		PRINT A				η_c %
	3	E CODE	065	PAPER ADVANCE			
	4		0	FILLER			
	5		0				
	6		0				
	7		0				
	8		↑( )( )				
	9		1				
77	0		7	$\dot{w}$ (lbm/s)			
	1		PRINT A				$\dot{w}$
	2	E CODE	065	PAPER ADVANCE			
	3		SET D.P	SET D.P. TO ZERO			
	4		0				
	5		↑( )( )				
	6		1				
	7		8	HP			
	8		PRINT A				HP
	9	E CODE	176	1 LINE OF DOTS			
78	0		↑( )( )				
	1		1				
	2		3				
	3		x				
	4		↑( )( )				
	5		0				
	6		4	c_p			
	7		=				
	8		$\sqrt{\ }$				
	9		x				
79	0		↑( )( )				
	1		1				
	2		0	N_u			
	3		x	U_T (ft/s)			
	4		PRINT X				U_T
	5		7				
	6		2				
	7		0				
	8		÷				
	9		π				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
800		÷				
1		↑( )( )				
2		1				
3		5	D_T			
4		=	N(rpm)			
5		PRINT A				N
6	E CODE	176	1 LINE OF DOTS			
7		SET D.P.	Set D.P to 3			
8		3				
9		1				
810		−				
1		↑( )				
2		7	$(r_1)_I$			
3		÷				
4		2				
5		=				
6		↑( )( )				
7		x				
8		1				
9		5	$D_T \rightarrow (\ell_1)_I$ (in)			
820		PRINT A				$(\ell_1)_I$
1		1				
2		−				
3		↑( )( )				
4		7				
5		3	$(r_3)_{Jmax}$			
6		÷				
7		2				
8		=				
9		↑( )( )				
830		x				
1		1				
2		5	$D_T \rightarrow (\ell_3)_{JMAX}$ (in)			
3		PRINT A				$(\ell_3)_{JMA}$
4	ECODE	176	1 LINE OF DOTS			
5		SET D.P.	Set D.P. to 4			
6		4				
7		HALT	END OF CALCULATIONS			
8						
9						
840						
1						
2						
3						
4						
5						
6						
7						
8						
9						

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MAIN STORAGE BOOKKEEPING

REGISTER	CONTENTS 1	CONTENTS 2	CONTENTS 3
00	R_G		
1	γ		
2	$\gamma - 1$		
3	$\gamma/(\gamma-1)$		
4	c_p		
5	$1/(\gamma-1)$		
6	$(\gamma-1)/\gamma$		
7	–		
8	$\cot(\beta_{1T})_I$		
9	–		
10	N_u		
1	$\dot{m}_{REF}$		
2	η_c		
3	T_0		
4	P_0		
5	$D_T = 2 R_T$		
6	$\dot{m}$		
7	$\dot{w}$		
8	HP		
9			
20			
1			
2			
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4			
5			
6			
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30			
1			
2	SEE NEXT PAGE		
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4			
5			
6			
7			
8			
9			
40			
1			
2			
3			
4			
5			
6			
7			
8			
9			

PROGRAM: 511 PAGE: S 2 of 2 DATE 4/73 BY: VA

MAIN STORAGE BOOKKEEPING

REGISTER	CONTENTS 1	CONTENTS 2	CONTENTS 3
50	β_{1T}		
1	r_1		
2	D_{RT}		
3	σ_{RT}		
4	λ		
5	Ω		
6	η_S		
7	k_1		
8	k_3		
9	β_{2T}		
60	T_{t1}/T_0		
1	P_{t1}/P_0		
2	T_1/T_0	STAGE DATA, 32 REGISTERS WHICH MUST BE	
3	p_1/P_0	READ ON ONE SIDE OF A MAGNETIC CARD	
4	—	FOR USE IN PROGRAM 512. (SEE OP. INSTR.	
5	$\Delta T_W/T_0$	PROGRAM 511)	
6	T_{t3}/T_0		
7	$\Delta\beta_T = \beta_{1T} - \beta_{2T}$		
8	—		
9	P_{t3}/P_0		
70	—		
1	T_3/T_0		
2	p_3/P_0		
3	r_3		
4	—		
5	$Z_J = Nu^2 \cot^2(\beta_{1T})_J/2$		
6	$Nu_1 = Nu \cot(\beta_{1T})_J/\sqrt{\gamma-1}$		
7	$\tan\beta_{1T}$		
8	$\tan\beta_{2T}$		
9	Υ_T		
80	$(\beta_{1T})_{J-1}$		
1	$(\lambda)_{J-1}$		
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

PROGRAM: 511 MULTI-STAGE IMPULSE AX-CO PAGE: S 1 OF 1 ; DATE: 4/73 ; BY: VA

SCRATCH PAD MEMORY STORAGE

0	1	2	3	4
$b=[1-(r_1)_J^2](K_1)_J \cot(\beta_{1T})_J$	X_T^2	X_T^2+1	$2\sigma_T/(X^2+1)$	$1-\lambda \frac{\tan\beta_{2T}}{\tan\beta_{1T}}$

5	6	7	8	9
$-\lambda^4 Z_J$	Identifier	$(r_1)_I$		

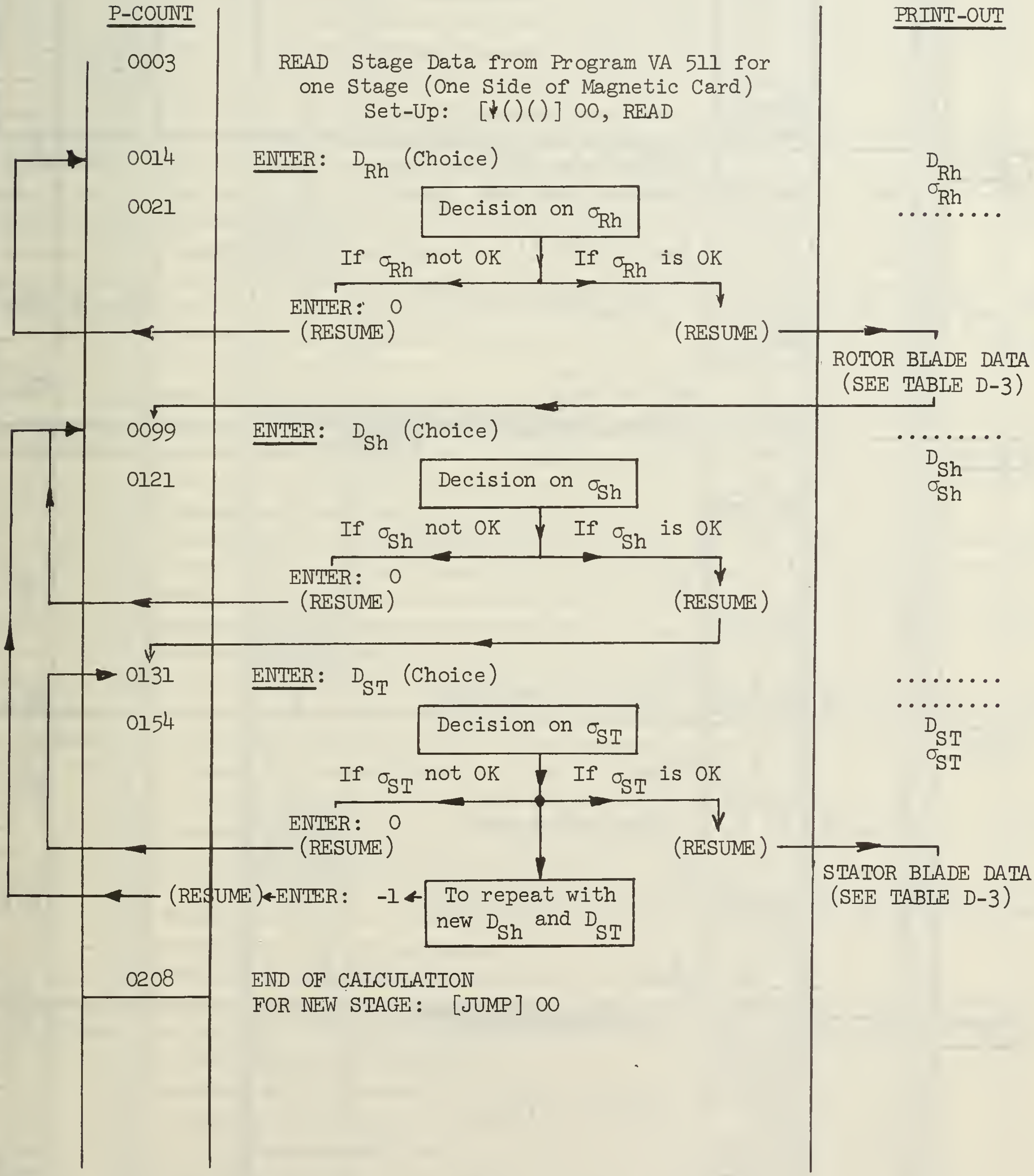
M.H.V. 1/27/73

APPENDIX C: PROGRAM VA 512 FOR
MONROE 1880-22 PROGRAMMABLE CALCULATOR

BLADING DATA OF MULTI-STAGE AXIAL
COMPRESSOR WITH IMPULSE BLADINGS
(USED IN CONJUNCTION WITH PROGRAM VA 511)

OPERATING INSTRUCTIONS PROGRAM VA 512 (MONROE 1880-22 CALCULATOR)

BLADING DATA OF STAGES OF MULTI-STAGE AXIAL
COMPRESSOR WITH IMPULSE BLADING
(Set-Up: LOAD MAGNETIC CARDS OF PROGRAM AT BRANCH PT. 00)



STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
	0		SET D.P.				
	1		4				
	2		HALT	READ DATA FROM MAG. CARD (REG. 0-31) PROG. VA 511			
	3		↑( )( )				
	4		0				
	5		1	r_1			
	6		↓( )				
	7		0			$r_1 \to 0$	
	8		BRANCH				
	9		IND/SYMB				
	0		+	TO S.R. β_1, β_2 FOR β_{1h}, β_{2h}			
	1	a^x	IND/SYMB	SYMBOLIC ADDRESS $[a^x]$			
	2		a^x				
	3		HALT	D_{Rh} (CHOICE)	D_{Rh}		
	4		↓( )				
	5		5	PRINT A		$D_{Rh} \to 5$	D_{Rh}
E=0	6		BRANCH				
	7		IND/SYMP				
	8		X	TO S.R. σ_{Rh}			σ_{Rh}
	9		HALT	IF σ_{Rh} O.K → [RESUME]; IF NOT: ENTER "0"			
	0		JUMP	→ [RESUME]			
	1		=				
	2		IND/SYMB				
	3		a^x				
	4		↑( )				
	5		0	r_1			~~#~~
	6		PRINT A				r_1
	7		↑( )				
	8		5	D_{Rh}			-
	9		PRINT A				D_{Rh}
	0		↑( )				
	1		6	σ_{Rh}			
	2		PRINT A				σ_{Rh}
	3	ECODE	065	PAPER ADVANCE			
	4		↑( )				
	5		7	β_{1h}			
	6		PRINT A				β_{1h}
	7		↑( )				
	8		8	β_{2h}			
	9		PRINT A				β_{2h}
	0	E CODE	065	PAPER ADVANCE			
	1		BRANCH				
	2		IND/SYMB				
	3		$\sqrt{\ }$	S.R. α_2, T_2/T_0			
	4		BRANCH				
	5		IND/SYMB				M_{v1h}
	6		X	S.R. M_{v1}, M_{w1}, M_{w2}			M_{w1h} M_{w2h}
	7	ECODE	176	1 LINE OF DOTS			
	8		0				
	9		0				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		2	2			
1		×				
2		↑( )( )				
3		0				
4		1	r_1			
5		+	$2r_1$			
6		1				
7		÷	$1+2r_1$			
8		3				
9		=	$r_1' = \frac{1}{3}(1+2r_1)$			
0		↓( )				
1		0				
2		PRINT A				r_1'
3		BRANCH				
4		IND/SYMB				
5		Φ	PRINT-OUT DATA AT r_1' (D_R', σ_R', β_1', β_2', M_{V1}', M_{W1}'			M_{W2}'
6		2	2			
7		+				
8		↑( )( )				
9		0				
0		1	r_1			
1		÷	$2+r_1$			
2		3				
3		=	$r_1'' = \frac{1}{3}(2+r_1)$			
4		↓( )				
5		0				
6		PRINT A				r_1''
7		BRANCH				
8		IND/SYMB				
9		Φ	PRINT-OUT DATA AT r_1'' (D_R'', σ_R'', β_1'', β_2'', M_{V1}'', M_{W1}'', M_{W2}''			
0		1				
1		↓( )				
2		0				
3		PRINT A				$r_{T=1}$
4		BRANCH				
5		IND/SYMB				
6		Φ	PRINT-OUT OF TIP DATA (D_{RT}, σ_{RT}, β_{1T}, β_{2T}, M_{V1}, M_{W1T}, M_{W2T}			
7		0				
8		0				
9		0				
0	1	IND/SYMB	SYMBOLIC ADDRESS 1			
1		1				
2		↑( )( )				
3		2				
4		3	r_3			
5		↓( )				
6		0			$r_3 \to 0$	
7		HALT	ENTER: D_{sh} [CHOICE]			
8		↓( )				
9		1			$D_{sh} \to 1$	

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	STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
	0		↓( )( )				
	1		4				
SYMB. ADD. 1	2		0			$D_{Sh} \rightarrow 40$	
	3		BRANCH				
	4		IND/SYMB				
	5		√	TO S.R. α_2			
	6		BRANCH				
	7		IND/SYMB				
	8		⤴	TO S.R. σ_S			
	9	ECODE	176	1 LINE OF DOTS			
	0		↑( )				
	1		1	D_{Sh}			
	2		PRINT A				D_{Sh}
	3		↑( )				
	4		2	σ_{Sh}			
	5		↓( )( )				
E=0	6		4				
	7		1				
	8		PRINT A				σ_{Sh}
	9		HALT	IF σ_{Sh} OK → [RESUME]; IF NOT ENTER "0"			
	0		BRANCH	& [RESUME]			
	1		=				
	2		IND/SYMB				
	3		1				
	4	2	IND/SYMB	SYMBOLIC ADDRESS 2			
S.A.2	5		2				
E=0	6		1				
	7		↓( )				
	8		0			$r_T = 1$	
	9		HALT	ENTER: D_{ST} [CHOICE]			
	0		↓( )				
	1		1			$D_{ST} \rightarrow 1$	
E=-1	2		↓( )( )				
	3		4				
	4		2			$D_{ST} \rightarrow 42$	
	5		BRANCH				
	6		IND/SYMB				
	7		√	TO S.R. α_2			
	8		BRANCH				
	9		IND/SYMB				
	0		⤴	TO S.R. σ_S			
	1	ECODE	176				
	2		176	2 LINES OF DOTS			
	3		↑( )				
	4		1	D_{ST}			
	5		PRINT A				D_{ST}
	6		↑( )				
	7		2	σ_{ST}			
	8		↓( )( )				
	9		4				

E=0 TO S.A.2

E=-1 TO S.A.1

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		3			$\sigma_{ST} \to 43$	
1		PRINT A				σ_{ST}
2		HALT	IF σ_{ST} OK → [RESUME]; IF σ_{ST} NOT OK			
3		JUMP	ENTER "0" → [RESUME]; IF σ_{ST}			
4		=	AND σ_{sh} HAVE TO BE CHANGED			
5		IND/SYMB	ENTER "-1" → [RESUME]			
6		2				
7		JUMP				
8		—				
9		IND/SYMB				
0		1				
1	ECODE	065	PAPER ADVANCE			
2	ECODE	065	PAPER ADVANCE			
3		↑( )( )				
4		2				
5		3	r_3			
6		↓( )				
7		0			$r_3 \to 0$	
8		BRANCH				
9		IND/SYMB				
0		=	TO S.R. STATOR BLADE DATA FOR $r = r_3$		PRINT	-OUT
1		2				
2		×				
3		↑( )( )				
4		2				
5		3	r_3			
6		+				
7		1				
8		÷				
9		3				
0		=	r_3'			
1		↓( )				
2		0				
3		BRANCH				
4		IND/SYMB				
5		=	TO. S.R. STATOR BLADE DATA FOR $r = r_3'$		PRINT-	OUT
6		2				
7		+				
8		↑( )( )				
9		2				
0		3	r_3			
1		÷				
2		3				
3		=	r_3''			
4		↓( )				
5		0				
6		BRANCH				
7		IND/SYMB				
8		=	TO S.R. STATOR BLADE DATA FOR $r = r_3''$		PRINT	-OUT
9		0	FILLER			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
	0		1				
	1		↓( )				
	2		0			$r=1 \rightarrow 0$	
	3		BRANCH				
	4		IND/SYMB				
	5		=	TO S.R. STATOR BLADE DATA FOR $r = r_T = 1$	P	RINT-OU	T ✓
	6		HALT				
	7		0				
	8		0				
	9		0				
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
2 1 0	+	IND/SYMB	SYMBOLIC ADDRESS +			
1		+				
2		↑( )				
3		0	r			
4		x				
5		↑( )( )				
6		2				
7		7	$\tan\beta_{1T}$			
8		=	$\tan\beta_1$			
9		↓( )				
0		1			$\tan\beta_1 \rightarrow 1$	
1	ECODE	103	$\beta_1{}^R$			
2		R→°	$\beta_1{}^\circ$			
3		↓( )				
4		7			$\beta_1 \rightarrow 7$	
5		SIN/COS				
6		2ND FCT	$\cos\beta_1$			
7		↓( )				
8		3			$\cos\beta_1 \rightarrow 3$	
9		↑( )				
0		0	r			
1		−				
2		(				
3		1				
4		÷				
5		↑( )	SUBROUTINE			
6		0	r β_1, β_2			
7		)	$1/r$ EQ'S. 6 & 7			
8		÷	$r - 1/r$ SYMB ADDRESS +			
9		↑( )( )				
0		0				
1		4	λ			
2		x	$\lambda(r - 1/r)$			
3		↑( )( )				
4		2				
5		7	$\tan\beta_{1T}$			
6		+	$\lambda(r - 1/r)\tan\beta_{1T}$			
7		(				
8		↑( )( )				
9		2				
0		8	$\tan\beta_{2T}$			
1		÷				
2		↑( )				
3		0	r			
4		)	$\frac{1}{r}\tan\beta_{2T}$			
5		=	$\tan\beta_2$			
6		↓( )				
7		2			$\tan\beta_2 \rightarrow$	2
8	ECODE	103	$\beta_2{}^R$			
9		R→°	$\beta_2{}^\circ$			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
260	0		↓( )				
	1		8	SUBROUTINE β_1, β_2		$\beta_2 \to 8$	
	2		SIN/COS	SYMB. ADD. +			
	3		2ND FUN	$\cos\beta_2$			
	4		↓( )				
	5		4			$\cos\beta_2 \to 4$	
	6		RESUME				
	7	X	IND/SYMB	} SYMBOLIC ADDRESS X			
	8		x	}			
	9		↑( )( )				
	0		0				
	1		4	λ			
	2		÷				
	3		↑( )				
	4		4	$\cos\beta_{2h}$			
	5		−	$\lambda/\cos\beta_{2h}$			
	6		(				
	7		1				
	8		−				
	9		↑( )				
	0		5	D_{Rh}			
	1		÷	$1 - D_{Rh}$			
	2		↑( )				
	3		3	$\cos\beta_{1h}$			
	4		)				
	5		x	SUBROUTINE			
	6		2	σ_{Rh} (EQ.44)			
	7		=	SYMB. ADDRESS X			
	8		INV				
	9		x				
	0		(				
	1		↑( )				
	2		1	$\tan\beta_{1h}$			
	3		−				
	4		(				
	5		↑( )( )				
	6		0				
	7		4	λ			
	8		x				
	9		↑( )				
30	0		2	$\tan\beta_{2h}$			
	1		)				
	2		)	↓( )( )			
	3		=	σ_{Rh} 3		$\sigma_{Rh} \to 35$	
	4		↓( )	5			
	5		6			$\sigma_{Rh} \to 6$	
	6		PRINTA	ECODE 176 1LINE DOTS			σ_{Rh}
	7		RESUME				
	8		0				
	9		0				

MONROE 1880

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
3 1 0	÷	IND/SYMB	SYMBOLIC ADDRESS ÷			
1		÷				
2		1	1			
3		−				
4		↑( )				
5		0	r			
6		÷	1-r			
7		(				
8		1	1			
9		−				
0		↑( )( )				
1		0	SUBROUTINE σ_R & D_R			
2		1	r_1 EQS. 48 & 11			
3		)	$1-r_1$ & PRINT ROUTINE			
4		x	$D_R, \sigma_R, \beta_1, \beta_2$			
5		(				
6		↑( )( )	SYMB. ADDRESS ÷			
7		0				
8		3	σ_{RT} ✓			
9		−				
0		(				
1		↑( )( )				
2		0				
3		1	r_1			
4		x				
5		↑( )( )				
6		3				
7		5	σ_{Rh}			
8		)	$r_1 \sigma_{Rh}$			
9		)	$\sigma_{RT} - \sigma_{Rh} r_1$			
0		−	$(\sigma_{RT} - r_1 \sigma_{Rh})\left(\frac{1-r}{1-r_1}\right.$			
1		↑( )( )				
2		0				
3		3	σ_{RT}			
4		÷				
5		↑( )				
6		0	r			
7		CHSGN	−r			
8		=	σ_R			
9		↓( )				
0		6			$\sigma_R \rightarrow 6$	
1		INV	$1/\sigma_R$			
2		x				
3		↑( )				
4		3	$\cos \beta_1$			
5		x				
6		↑( )( )				
7		2				
8		9	γ_T			
9		÷				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
36	0		↑( )				
	1		0	r			
	2		+				
	3		1				
	4		−	$1+\frac{1}{r}\frac{\cos\beta_1}{\sigma_R}\Upsilon_r$ SUBROUTINE			
	5		(	σ_R, D_R EQS. 48, 11			
	6		↑( )( )	PRINT D_R, σ_R, β_1, β_2			
	7		0	SYMB. ADD ÷			
	8		4	λ			
	9		×				
	0		↑( )				
	1		3	$\cos\beta_1$			
	2		÷				
	3		↑( )				
	4		4	$\cos\beta_2$			
	5		)				
	6		=	D_R			
	7		PRINT A				D_R
	8		↑( )				
	9		6	σ_R			
	0		PRINT A				σ_R
	1	ECODE	065	PAPER ADVANCE			
	2		↑( )				
	3		7	β_1			
	4		PRINT A				β_1
	5		↑( )				
	6		8	β_2			
	7		PRINT A				β_2
	8	ECODE	065	PAPER ADVANCE			
	9		RESUME				
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
3 9	0	√	IND/SYMB	SYMBOLIC ADDRESS √			
	1		√				
	2		2	2			
	3		x				
	4		↑(X)				
	5		2				
	6		9	Υ_T			
	7		÷				
	8		↑( )( )				
	9		0				
	0		4	λ			
	1		÷				
	2		↑( )				
	3		0	r			
	4		=	$\tan\alpha_2$			
	5	E CODE	103	$\tan^{-1} = \alpha_2{}^R$			
	6		R →°	α_2			
	7		↓( )( )				
	8		3				
	9		6			$\alpha_2 \to 36$	
	0		SIN/COS	$\sin\alpha_2$			
	1		↓( )( )	SUBROUTINE			
	2		3	α_2 & T_2/T_0			
	3		7	EQS. 13 & 25		$\sin\alpha_2 \to 37$	
	4		2ND FUN	$\cos\alpha_2$ SYMB. ADD √			
	5		↓( )( )				
	6		3			$\cos\alpha_2 \to 38$	
	7		8				
	8		÷				
	9		↑( )( )				
	0		0				
	1		4	λ			
	2		x	$\cos\alpha_2/\lambda$			
	3		=	$(\cos(\alpha_2)/\lambda)^2$			
	4		INV	$\lambda^2/\cos^2\alpha_2$			
	5		x				
	6		↑( )( )				
	7		2				
	8		5	$Z = \frac{Nu^2}{2}\cot^2\beta_{1T}$			
	9		CHSGN				
	0		+	$-\frac{\lambda^2}{\cos^2\alpha_2} Z$			
	1		↑( )( )				
	2		1				
	3		6	T_{t3}/T_0			
	4		=	T_2/T_0			
	5		↓( )( )				
	6		3				
	7		9			$T_2/T_0 \to 39$	
	8		RESUME				
	9						

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
4 4 0	α	IND/SYMB	{ SYMBOLIC ADDRESS α			
1		α				
2		↑( )( )				
3		1				
4		2	T_1/T_0			
5		√				
6		INV	$1/\sqrt{T_1/T_0}$			
7		x				
8		↑( )( )				
9		2				
0		6	$N_{u1} = (N_u/\sqrt{\gamma-1}) \cot \beta_{1T}$			
1		÷	M_{V1}			
2		PRINT X				M_{V1}
3		↑( )				
4		3	$\cos \beta_1$			
5		=	M_{W1}			
6		PRINT A				M_{W1}
7		↑( )( )				
8		3				
9		9	T_2/T_0			
0		√				
1		INV	$1/\sqrt{T_2/T_0}$ SUBROUTINE			
2		x	M_{V1}, M_{W1}, M_{W2}			
3		↑( )( )				
4		0	EQS. 37, 36, 38, 39			
5		4	λ SYMBOLIC ADDRESS α			
6		x				
7		↑( )( )				
8		2				
9		6	N_{u1}			
4 7 0		÷				
1		↑( )				
2		4	$\cos \beta_2$			
3		=	M_{W2}			
4		PRINT A				M_{W2}
5		RESUME				
6		0				
7		0				
8		0				
9		0				
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
48	0	Φ	IND/SYMB	SYMBOLIC ADDRESS Φ			
	1		Φ				
	2		BRANCH				
	3		IND/SYMB				
	4		+	TO S.R. β_1, β_2			
	5		BRANCH	SUBROUTINE ROTOR			
	6		IND/SYMB	BLADE DATA			D_R
	7		÷	TO S.R. σ_R, D_R AT r			σ_R
	8		BRANCH	SYMBOLIC ADDRESS Φ			β_1
	9		IND/SYMB				β_2
	0		$\sqrt{\ }$	TO. S.R. α_2 & T_2/T_0			
	1		BRANCH				
	2		IND/SYMB				M_{V1}
	3		X	To SR M_{V1}, M_{W1}, M_{W2}			M_{W1}
	4	ECODE	176	1 LINE OF DOTS			M_{W2}
	5		RESUME				
	6		0				
	7		0				
	8		0				
	9		0				
50	0	⤴	IND/SYMB	SYMBOLIC ADDRESS ⤴			
	1		⤴				
	2		↑( )( )	x			
	3		3	↑( )( )			
	4		8	$\cos\alpha_2$ 0			
	5		−	$\lambda\cos\alpha_2$ 4 [λ]			
	6		(	SUBROUTINE σ_S			
	7		1	1 EQ. 51			
	8		−	SYMB ADD ⤴			
	9		↑( )				
	0		1	D_S			
	1		)	$1-D_S$			
	2		x	$\lambda\cos\alpha_2 - [1-D_S]$			
	3		2				
	4		=	$2[\lambda\cos\alpha_2 - (1-D_S)]$			
	5		INV				
	6		x				
	7		↑( )( )				
	8		3				
	9		7	$\sin\alpha_2$			
52	0		=	σ_S			
	1		↓( )				
	2		2			$\sigma_S \rightarrow 2$	
	3		RESUME				
	4		0				
	5		0				
	6		0				
	7		0				
	8		0				
	9		0				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
53 0	=	IND/SYMB	SYMBOLIC			
1		=				
2		1	1			
3		−				
4		↑( )				
5		0	r			
6		÷	1 − r			
7		(				
8		1	1			
9		−				
0		↑( )( )				
1		2				
2		3	r_3 SUBROUTINE STATOR			
3		)	$1-r_3$ BLADE DATA			
4		×	$\frac{1-r}{1-r_3}$ SYMBOLIC ADDRESS =			
5		(				
6		↑( )( )				
7		4				
8		3	σ_{ST}			
9		−				
0		(				
1		↑( )( )				
2		2				
3		3	r_3			
4		×				
5		↑( )( )				
6		4				
7		1	σ_{sh}			
8		)	$r_3 \sigma_{sh}$			
9		)	$\sigma_{ST} - r_3 \sigma_{sh}$			
0		−	$(\sigma_{ST} - r_3 \sigma_{sh}) \frac{1-r}{1-r_3}$			
1		↑( )( )				
2		4				
3		3	σ_{ST}			
4		÷				
5		↑( )				
6		0	r			
7		CHSGN	−r			
8		=	σ_S			
9		↓( )				
57 0		2			$\sigma_S \to 2$	
1		BRANCH				
2		IND/SYMB				
3		√	TO S.R. α_2 & T_2/T_0			
4		↑( )				
5		0	r			
6		PRINT A				r
7		↑( )( )				
8		3				
9		7	$\sin \alpha_2$			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
58 0		÷				
1		2				
2		÷				
3		↑( )				
4		2	σ_s			
5		+				
6		1				
7		−	$1 + \sin\alpha_2 \frac{1}{2\sigma_s}$			
8		(				
9		↑( )( )				
0		0				
1		4	λ SUBROUTINE STATOR			
2		x	BLADE DATA (CONT. 1)			
3		↑( )( )	SYMBOLIC ADDRESS =			
4		3				
5		8	$\cos\alpha_2$			
6		)	$\lambda \cos\alpha_2$			
7		=	D_S			
8		PRINT A				D_S
9		↑( )				
0		2	σ_s			
1		PRINT A				σ_s
2	ECODE	065	PAPER ADVANCE			
3		↑( )( )				
4		3				
5		6	α_2			
6		PRINT A				α_2
7	ECODE	065	PAPER ADVANCE			
8		↑( )( )				
9		3				
0		9	T_2/T_0			
1		$\sqrt{\ }$				
2		INV	$1/\sqrt{T_2/T_0}$			
3		x				
4		↑( )( )				
5		2				
6		6	N_{u_1}			
7		÷				
8		↑( )( )				
9		3				
62 0		8	$\cos\alpha_2$			
1		x				
2		↑( )( )				
3		0				
4		4	λ			
5		=	M_{V2}			
6		PRINT A				M_{V2}
7		↑( )( )				
8		2				
9		1	T_3/T_0			

STEP		SYMBOL	COMMAND	COMMENTS		ENTER	STORE	PRINT
63	0		$\sqrt{\ }$	$\sqrt{T_3/T_0}$				
	1		INV	$1/\sqrt{T_3/T_0}$	(CONT.2)			
	2		×		SUBROUTINE STATOR			
	3		↑( )( )		BLADE DATA			
	4		2		S.A. =			
	5		6	Nu_1				
	6		×					
	7		(					
	8		↑( )( )					
	9		0					
64	0		4	λ				
	1		×					
	2		)	λ^2				
	3		=	M_{V3}				
	4		PRINT A					M_{V3}
	5	ECODE	065	PAPER ADVANCE				
	6	ECODE	176	1 LINE OF DOTS				
	7		RESUME					
	8							
	9							

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SCRATCH PAD MEMORY STORAGE

0	1	2	3	4
r	$\tan\beta_1$	$\tan\beta_2$	$\cos\beta_1$	$\cos\beta_2$
	D_{sh}	σ_s		
	D_s			
	D_{ST}			

5	6	7	8	9
D_{Rh}	σ_{Rh}	β_1	β_2	
	σ_R			

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MAIN STORAGE BOOKKEEPING

REGISTER	CONTENTS 1	CONTENTS 2	CONTENTS 3
00	β_{1T}		
01	r_1		
02	D_{RT}		
03	σ_{RT}		
04	λ		
05	Ω		
06	η_s		
07	k_1		
08	k_3		
09	β_{2T}		
10	T_{t1}/T_0		
11	P_{t1}/P_0		
12	T_1/T_0	READ FROM MAGNETIC	CARD OF DATA
13	p_1/p_0	OF PROGRAM 511 (32	REGISTERS, ONE
14	—	SIDE OF MAG. CARD)	
15	$\Delta T_W/T_0$	FOR EACH STAGE	
16	$\Delta T_3/T_0$		
17	$\Delta\beta_T = \beta_{1T} - \beta_{2T}$		
18			
19	P_{t3}/p_0		
20			
21	T_3/T_0		
22	p_3/p_0		
23	r_3		
24			
25	$Z = Nu^2 \cot^2\beta_{1T}/2$		
26	$Nu_1 = Nu \cot\beta_{1T}/\sqrt{\gamma-1}$		
27	$\tan\beta_{1T}$		
28	$\tan\beta_{2T}$		
29	γ_T		
30	$(\beta_{1T})_{J-1}$		
31	$(\lambda)_{J-1}$		
32			
33			
34			
35	σ_{Rh}		
36	α_2		
37	$\sin\alpha_2$		
38	$\cos\alpha_2$		
39	T_2/T_0		
40	D_{Sh}		
41	σ_{Sh}		
42	D_{ST}		
43	σ_{ST}		
44			
45			
46			
47			
48			
49			

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APPENDIX D: FORMS FOR PRINT-OUTS OF PROGRAMS VA 511 AND VA 512

PROGRAM VA511

TABLE D-1 :PRINT-OUT OF RESULTS OF STAGE DATA CALCULATIONS

CONFIGURATION # : ____________

STAGE#		STAGE#	
β_{1T}		β_{1T}	
D_{RT}		D_{RT}	
σ_{RT}		σ_{RT}	
λ		λ	
β_{2T}		β_{2T}	
$\Delta\beta_T$		$\Delta\beta_T$	
Ω		Ω	
η_S		η_S	
T_{t1}/T_0		T_{t1}/T_0	
P_{t1}/P_0		P_{t1}/P_0	
T_1/T_0		T_1/T_0	
P_1/P_0		P_1/P_0	
T_{t3}/T_0		T_{t3}/T_0	
P_{t3}/P_0		P_{t3}/P_0	
T_3/T_0		T_3/T_0	
P_3/P_0		P_3/P_0	
r_1		r_1	
k_1		k_1	
r_3		r_3	
k_3		k_3	

PROGRAM VA511

TABLE D-2 : PRINT-OUT OF RESULTS OF OVERALL COMPRESSOR PERFORMANCE

CONFIGURATION # : _______

Molecular Weight of Gas M
Specific Heat Ratio of Gas γ

. . . .

First Stage Data: Relative Tip Flow Angle β_{1T}
Hub/Tip Ratio r_1
Blockage Factor k_1

. . . .

Referred Tip Speed N_u
Referred Mass Flow Rate $\dot{m}_{REF}$

. . . .

. . . .

. . . .

Total Inlet Pressure (psia) P_0
Total Inlet Temperature (^{o}R) T_0
Tip Diameter of Stages (inches)

Overall Total Pressure Ratio
Overall Total-to-Total Efficiency (%)

Weight Flow Rate (lbm/s)

Blading Drive Power (HP)

. . . .

Peripheral Speed at Rotor Tip (ft/s)
Rotative Speed (rpm)

. . . .

Blade Height of First-Stage Rotor(in.)
Blade Height of Last Stator (in,)

. . . .

PROGRAM VA512

TABLE D-3 : PRINT-OUT OF BLADING DATA

CONFIGURATION #: ________ STAGE #: ______

ROTOR

HUB	r_h	
	D_{Rh}	
	σ_{Rh}	
	β_{1h}	
	β_{2h}	
	M_{V1}	
	M_{W1h}	
	M_{W2h}	
1/3 BLADE HEIGHT	r	
	D_R	
	σ_R	
	β_1	
	β_2	
	M_{V1}	
	M_{W1}	
	M_{W2}	
2/3 BLADE HEIGHT	r	
	D_R	
	σ_R	
	β_1	
	β_2	
	M_{V1}	
	M_{W1}	
	M_{W2}	
TIP	r_T	
	D_{RT}	
	σ_{RT}	
	β_{1T}	
	β_{2T}	
	M_{V1}	
	M_{W1}	
	M_{W2}	

STATOR

HUB	r_h	
	D_{Sh}	
	σ_{Sh}	
	α_{2h}	
	M_{V2}	
	M_{V3}	
1/3 BLADE HEIGHT	r	
	D_S	
	σ_S	
	α_2	
	M_{V2}	
	M_{V3}	
2/3 BLADE HEIGHT	r	
	D_S	
	σ_S	
	α_2	
	M_{V2}	
	M_{V3}	
TIP	r_T	
	D_{ST}	
	σ_{ST}	
	α_{2T}	
	M_{V2}	
	M_{V3}	

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